

DOE/NOAA/OTEC--18

DE82 021822

OCEAN THERMAL ENERGY CONVERSION PROGRAM

DOE/NOAA/OTEC-18

Distribution Category UC-64

FIBER-REINFORCED-PLASTIC COLD-WATER-PIPE

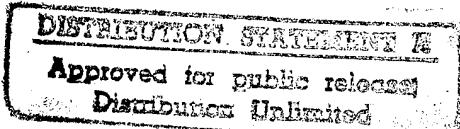
TEST PLAN

Final Report

Prepared for:

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October 24, 1978



DHS QUALITY INSPECTED 2/

Contract No. NDBO 03-78-G03-0507

DEPARTMENT OF DEFENSE  
ARMED FORCES TECHNICAL EVALUATION CENTER  
TECHNICAL REPORT 66

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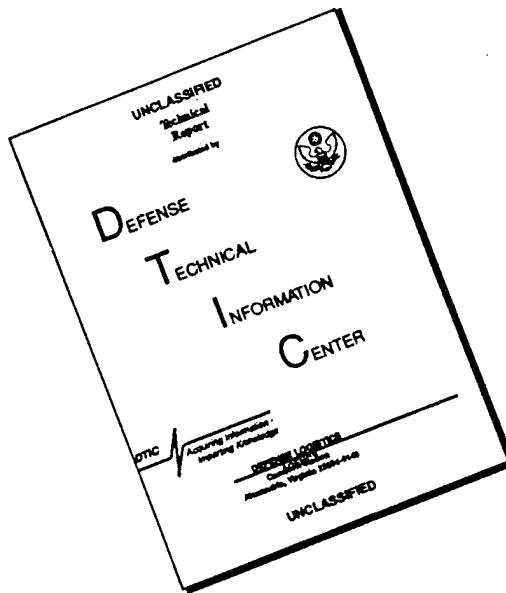
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## 1.0 INTRODUCTION

Fiber Reinforced Plastics offer great advantages when used in complex applications which must survive severe environmental conditions. It is light in weight, flexible in design and construction, and highly corrosion resistant, offering the promise of new, highly cost effective and low maintenance process systems. The latent potential of FRP attributes has only been tapped.

There are many areas of variation between FRP and other materials of construction, however, and they must be carefully considered in equipment design. Some of the characteristics of FRP will appear as liabilities, when, in fact, with the use of new design approaches, they become profound assets. One such characteristic is the variability of the product itself. Fiber Reinforced Plastic is actually produced as the equipment is being formed. This variability results in less well-defined physical properties for any particular composite. Also a wide range of physical properties are possible with different laminate constructions. In addition to this, Fiber Reinforced Plastic laminates have different physical properties in different directions, physical properties which also vary with exposure and time. The consequence of this variability is a greater need of materials testing for laminate optimization to the particular application and to establish new laminate performance for these applications. This need for materials testing is nowhere more appropriate than in the application of Fiber Reinforced Plastics to a complex design such as the OTEC Cold Water Pipe.

In the following test management plan, a flexible test configuration and procedure is proposed in which Fiber Reinforced Plastic scale models of the actual cold water pipe and joint configurations can be exhaustively and cost effectively tested. The test apparatus has been designed to produce both static and dynamic loads in the scale models to accurately simulate any loading condition to which the actual cold water pipe could be subjected. More specifically, the apparatus can impose virtually any combination of tensile, compressive, and flexural principal stresses in a CWP test model in either a static or dynamic loading mode. The test models will be immersed in water in order to simulate more closely the actual marine environment. The basic statistical analysis has been designed to afford the test engineer a capability of determining when a test series has achieved a given statistical validity, thus avoiding the costs of needless tests. The entire test program has been designed with the object of accurately simulating real conditions: the

## 1.0 INTRODUCTION (continued)

marine environment through immersion of the test model in a water bath, the dynamic environment through careful control of a well-defined statistical description of the pipe-hull interaction, and the CWP through exact scaling of the actual structure. Every effort has been made to obtain high test repeatability through quality control and consistency in apparatus and procedures. Accuracy will be assured by regular and careful calibrations to valid standards.

By first using small models, comparative and developmental testing can be performed to optimize materials, pipe and pipe joint designs, and develop long-term materials performance data for purposes of pipe design. Later, more costly, large-scale testing can be performed to reaffirm scalability and increase confidence in the actual design. This combination of small-scale and large-scale testing as a part of any development program has traditionally produced the most accurate results in the shortest period of time and at the lowest cost possible.

## 2.0 SCOPE OF WORK

The tests included in this management plan have been designed to evaluate joint performance and to obtain the engineering properties of Fiber Reinforced Plastics (FRP) that are germane to the development of an OTEC FRP Cold Water Pipe. Both material property tests and tests of cold water pipe joint configurations using FRP are planned. Engineering properties of interest include: ultimate tensile strength, tensile modulus of elasticity, flexural strength, flexural modulus of elasticity, fatigue strength at an expected 30-year service life, and Poisson's Ratio.

The tests selected have been chosen and designed to satisfy the following requirements: establish initial fatigue test stress levels through fracture testing of the various candidate joint and laminate configurations, evaluate the fatigue resistance of Fiber Reinforced Plastic joints and laminates subjected to a non-stationary random loading, evaluate the long-term degradation of material properties in a marine environment, design of a cold water pipe, and obtain a baseline of acoustical emission data for in-service nondestructive monitoring of FRP Cold Water Pipe performance.

As an aid to planning and budgetary control, the test costs and schedules are presented in terms of four options, each option including a wider scope of testing effort than its predecessor. Option One, the most basic of the four options, covers axial fracture and fatigue tests of three joint configurations. Option Two adds to the tests of Option One flexural fracture and fatigue testing of the same three joints. Option Three introduces fracture and fatigue tests of two FRP laminate configurations, and Option Four, the flexure testing of those same laminates. The final long-term fatigue test of each test option will be made on the best surviving joint or laminate configuration of that test series.

### 3.0 SUMMARY OF METHODS

#### 3.1 General

The test method is both simple and straight forward: a battery of filament wound pipes scaled to the actual size of the cold water pipe and immersed in a water bath (Dwg. FSE 1074-03) will be subjected to a specified combination of principal stresses through the application of hydrostatic or hydrodynamic pressure. It has been indicated that FRP composites are relatively insensitive to thickness effects (16). Control of the tests will be maintained by a microcomputer which will signal when failure of the models occur or when system integrity checks are not met. Pressure and strain measurements will be made by transducers attached to the test models and that data subjected to a preprogrammed error and statistical analyses by the microcomputer before being directed to permanent floppy disk data storage. Accuracy of the measured data shall be maintained by redundancy in the use of transducers, by system integrity checks made by the microcomputer, and by strict calibration of the pressure transducers before and after each test.

Preparation of all test models shall be the same; the same test bath, process control systems, and data acquisition equipment will be used. The test methods shall be the same for all tests, the procedures differing only in the dynamics of the applied loads. For each test, the gradual loss of stiffness in the test model, as measured by the modulus of elasticity, shall be the governing criterion of failure, except in the case of joint testing where shear at the joint interface will be considered as failure.

The testing process will be governed by two statistical parameters specified by NOAA: a maximum allowable percentage of error (50%) and the desired level of confidence (70%). At the completion of each test the data obtained from that test and from all previous tests in that series shall be subjected to a comprehensive statistical analysis program to determine if the specified statistical parameters have been met. Each test series shall be continued until the data satisfies the statistical requirements of the test program.

### 3.1 General (continued)

A particular feature of this testing program will be the optional use of acoustic emission monitoring as a method of evaluating the long-term degradation of physical strength of a test model. This method is especially applicable in the joint test where direct strain measurements are difficult to obtain and even more difficult to interpret. The use of acoustic emission monitoring shows great promise for future in-service structural evaluation. Using acoustic emission monitoring a structural defect in the Cold Water Pipe can be detected as soon as it occurs and then continuously monitored throughout its development. The use of acoustic emission monitoring during the test program is expected to provide a baseline of information for such future evaluations.

### 3.2 Fracture Tests

A series of fracture tests will be made to establish Poisson's Ratio, moduli of elasticity, and ultimate strength of FRP joints and laminates. These results will then be used to establish initial stress levels for fatigue tests which follow. The fracture test procedure shall consist of increasing the axial stress in the test model at a constant rate of strain (0.1- min) until failure occurs. Data to be obtained during this test includes stress and strain at one second intervals to failure. Regression analysis shall be applied to the final data as appropriate. These tests shall be performed with no pressure differential across the specimen wall.

### 3.3 Fatigue Tests

Fatigue tests shall be conducted to determine a predictable fatigue strength for candidate FRP laminates and joint configurations for a 30-year service life in a marine environment. The procedure shall consist of the concurrent application of a random cycling axial load to the test models in such a way as to simulate the interaction of ocean forces and hull-to-pipe dynamics for an in-service Cold Water Pipe. The test shall be repeated at each of three different stress levels until the data obtained at each stress level meet the statistical requirements for the test. Strength distribution at an equivalent 30-year service life shall then be determined using the statistical methods outlined below and the results plotted as shown in Figure 5.

### 3.4 Flexure Tests

A series of flexure tests shall be conducted to determine the flexural modulus of elasticity, the ultimate strength of the composite in flexure, and the fatigue strength in flexure. Provision shall be made to apply hydraulic loads to the ends of the test specimens while the internal section of the test specimen is supported by two saddles equidistant from the center (Dwg. FSE 1074-03). By forcing both ends down at the same time the test specimen shall be subjected to pure bending. For the fatigue tests, these loads can be cycled according to the same random load signal generated for the preceding fatigue tests. In each test the internal pressure in the test specimen shall be maintained at -0.5 psi differential with no pressure in the end caps.

### 3.5 End Term Fracture Tests

The fracture tests described in Section 3.2 will be repeated at the termination of the test program using specimens preconditioned in accordance with Section 6.1 in order to establish the long-term degradation of material properties.

## 4.0 TEST MODELS

### 4.1 Joint Configurations

Two different joint configurations will be tested: a flanged connection with a rubber gasket and stainless steel bolts; and a butt and strap welded joint with a balanced interior overlay. Drawing FSE 1074-01 shows these joint configurations in detail. Test space is available for a third joint configuration which will be considered optional in this test plan.

### 4.2 FRP Laminate Configurations

Drawing FSE 1074-01 also shows the FRP laminate for the cold water pipe test model. Testing space for two FRP laminate configurations are available; the second will be considered optional in this test plan.

### 4.3 End Caps

Drawing FSE 1074-01 shows the detailed construction of the end caps which are to be used for both joint and laminate testing.

### 4.4 Internals

Drawing FSE 1074-02 shows the design and construction of the steel bulkheads which fit inside the test models and separate the pressure in the end caps from the vacuum pressure inside the test model.

### 4.5 Tolerances

The tolerances of all fabrication will conform to the following requirements (13):

Pipe Diameter	$\pm 0.005$ inches
Pressure	$\pm 1\%$ of indicated value
Strain Rate	0.1 inch per inch per minute $\pm 25\%$
Time	$\pm 1\%$
Calipers	$0.001$ inches $\pm 0.000$
O-ring grooves	$\pm 0.001$ inches

#### 4.5 Tolerances (continued)

Test model conformance with these requirements shall be checked each time a test model is brought onto the work platform for preparation. Twenty-five measurements of inside diameter and wall thickness will be made at equally spaced intervals around the circumference of the pipe and the means and standard deviations of these various sets of measurements calculated. The standard deviation of the mean shall then be calculated and the probability of that deviation from the mean compared to the statistical requirements of the test program. Any test models not meeting these requirements will be rejected.

## 5.0 APPARATUS

### 5.1 Test Bath

The test bath may contain either sea water or fresh water, providing only that it has a depth sufficient to cover the top of the test model by 18". A bed of sand 6" thick should cover the bottom of the test bath and provide a smooth surface upon which the test model can lay. The area of the bath should be sufficiently large to include not only the model being tested but also the models which will be required for the end-term fracture test. It is not necessary that the temperature of the test bath be controlled; however, wide fluctuations in the temperature should be avoided if possible. Likewise, the contents of the test bath can be either salt water or fresh water, although if a salt water bath is chosen a salinity of 32 to 35 parts per million is recommended.

### 5.2 Hydraulics

The driving force in the test models shall be provided by a high pressure hydraulic system which takes water from the test bath, pressurizes it, and feeds it to a high-pressure header mounted along the length of the test bath (Drawing FSE 1074-03). Each test specimen is connected to the high-pressure header by a flexible hose and manual valve. The high-pressure water provides the means for pressurizing the end caps of the test models thus inducing axial stress. An electro-pneumatic servo controlled flow valve controls the flow, and hence the pressure, from the pressure pump to the header. A second electro-pneumatic servo controlled flow valve controls the release of pressure from the test models allowing the discharge of pressurized water back into the test bath. Both electro-pneumatic valves are controlled by a process control program in the microcomputer. A relief valve prevents excessive pressure in the system. Thus, a specified hydrostatic or hydrodynamic pressure is applied to the header which, in turn, provides the driving force for the test.

A second header, adjacent to the high-pressure header and extending the length of the test bath, provides a vacuum pressure from the intake manifold of the pressure pump. This vacuum is applied to the internal section of the test model through a flexible hose and manual valve connecting the vacuum header and the test model.

### 5.3 Process Control

Because of the varied tests which must be conducted, the complexity of the loading conditions, and the large volume of data that must be gathered, a microcomputer is considered essential. The microcomputer will be capable of providing complete process control and data acquisition, excluding acoustic emission data acquisition. A variety of microcomputers are available on the market today which have this capability. The microcomputer system will do a variety of things: it will accept the control program from the test engineer through a keyboard and then display the test parameters on the screen of a CRT for verification; it will control the test by issuing commands to the set point as part of a closed loop control, and it would also issue the proper control sequence to run the test; at the peak of each cycle it will calculate the modulus of elasticity of each test model and store that value, and at the end of 30 minutes it will take the accumulated test data, the number of cycles, as well as the number of moduli of elasticity, and print this information on a line printer, as well as recording the information on a mass storage disk. The microcomputer system will also be available for on- or off-line data reduction through either individually programmed instructions or off-the-shelf type programs to perform error and statistical analyses, which could then be output onto an X-Y recorder, a line printer, or a CRT screen.

As part of the process control program the microcomputer will generate a random load control signal for the fatigue test. The random load signal generated is a waveform having a period of 16 seconds and random peak loads having an underlying Rayleigh distribution and root mean square (RMS) levels having a normal distribution. The standard deviation of the Rayleigh distribution is equal to the root mean. Thus, as the RMS level increases, the standard deviation of the Rayleigh distribution of peak loads also increases. The load spectrum thus generated, with appropriate programming of the root mean square levels, will match exactly the field load spectrum if found log linear. In the absence of any specific information, Lipson & Sheth (1) recommend that random load spectra in the field be assumed to have a log linear relationship. The microcomputer will automatically compare the pressure in the high-pressure header with the desired pressure corresponding to the level of the load signal.

### 5.3 Process Control (continued)

and issue a feedback signal to the set point control of the appropriate electro-pneumatic servo controlled flow valve. An appropriate clipping ratio will be incorporated in this program so that the generated random load signal from the microcomputer will not exceed a desired maximum value.

The microcomputer will also be programmed to provide various integrity checks of the system process (see Appendix 13.3). Double transducers will be used for both pressure measurement and strain measurements. In each case, the difference in the two measurements will be compared to a maximum allowable value. If this value is exceeded a warning signal will be displayed on the console of the control panel. Additionally, when the tangent modulus of elasticity falls to a specified level another warning signal will be displayed indicating failure of the test model.

### 5.4 Data Acquisition

Data Acquisition shall be provided by two main systems. The first is the microcomputer. In addition to providing process control, the microcomputer will also direct data onto permanent storage. Primary input to the microcomputer will be pressure, strain, and temperature. The temperature will be monitored only so that the operator will be able to detect large fluctuations. Temperature, as such, will not be a controlled test variable.

After performing the appropriate error analysis, the microcomputer will direct stress data, strain data, and cycles data to the memory. The data acquisition hardware will consist of an X to Y plot, a printer, and a floppy disk. This hardware will also interface with the second data acquisition system, the acoustic emissions monitoring system (Figure 2). The acoustic emission data acquisition will include a cumulative acoustic emission burst count versus real time, the number of acoustic emission bursts versus the decible and computed felicity effects versus time. In addition, acoustic emission data will be correlated with the data taken by the microcomputer so that acoustic emission and stress/strain data can be compared in real time.

## 5.5 Peripheral Equipment

In addition to the equipment and apparatus described above, a variety of other accessory equipment will be required. At one side of the test bath a large area for test model build-up should be located. This area should be large enough to accomodate three or four test models, three or four pair of end-caps, an equal number of steel bulkhead apparatus, and all the necessary equipment for making butt and strap joints. Provision should be made for first aid equipment and an eyewash in the immediate area of the working platform. To one side of the working platform should be located a curing oven of a size large enough to accomodate one test model with the end-caps in place. This oven shall consist of a plenum, a heater, a blower, a mixing valve, and associated duct work. An overhead rail should extend from the working platform across the test bath with a chain hoist and a nylon strap sling for moving test models from the working area to the test bath. Space should also be provided for a desk and administrative working area for the test engineer. This could be located adjacent to the process control and data acquisition platform overlooking the test bath.

The process control system operates by metering compressed air through a servo valve to a control valve which regulates the flow of high-pressure water to or from the test models. This requires a compressor, regulator, pressure accumulator, and pneumatic lines be installed to provide compressed air to the process control system. Drawing FSE 1074-04 shows this pneumatic system.

## 6.0 CONDITIONING

### 6.1 Pre-soaking

Throughout the duration of the testing program a supply of test models adequate to complete the End-Term Fracture tests shall be kept immersed in the test bath. These will be used to test the long-term degrading effects of such exposure.

### 6.2 Post-curing

The test models shall be lowered into the curing oven as soon as the butt and strap joints are of sufficient strength to allow movement of the model. Air drawn in from the outside and heated in the heater shall be mixed with ambient air in the mixing valve and directed through the plenum to be exhausted outside. The temperature shall be maintained at the appropriate level and for the appropriate duration of time as specified by the manufacturer of the resin.

## 7.0 TEST PROCEDURES

### 7.1 Facilities Buildup

Once authorization for the test program is received and the test site has been chosen, the facility will be inspected to determine what additional equipment will be necessary to conduct the test program. Lease or rental agreements are preferred to open purchase, unless it can be clearly shown that such purchase is more economical. Assembly of the test apparatus will be under the supervision of the test engineer and shall be in conformance with this test management plan and the drawings contained herein. Once the apparatus is assembled and ready, an initial proof test shall be made to determine that the systems are operating normally. In this test a sample FRP test model will be tested to fracture. All composites of the test apparatus, process control, and data acquisition systems shall be tested to insure normal operation, and if necessary, adjustments or replacements will be made before commencement of the test program. The test engineer shall take this opportunity to "value engineer" the test management plan and facility. Cost effective improvements in the test program are encouraged in order to avoid future cost or delay in the testing process. The test engineer shall also use the proof testing to develop efficient record-keeping procedures.

### 7.2 Test Methods

#### 7.2.1 Preparation of test models

A visual check of each test specimen will be made for defects, cracks, crazing or other damage which could be detrimental to the testing program. Using a calipers, measure the wall thickness at a minimum of 25 locations equally spaced around the circumference of the test specimen. The inside diameter shall also be measured at a minimum of 25 places equally spaced around the circumference and the means and standard deviations of these measurements calculated. If the specimen does not meet the minimum required statistical requirements of the test program, the specimen shall be rejected. Assuming the test specimen to be within limits, slide the steel bulkheads carefully into the specimen taking care that the steel edges do not scratch

### 7.2.1 Preparation of test models (continued)

otherwise mar the inside of the test specimen and that the O-ring seals are in place and secure. If a joint configuration is to be tested, first attach the three strain transducers across the interior joint and tape the wires to the inside wall. With the steel bulkheads in place bring the two end-caps against the ends of the test specimen and attach the vacuum pressure line. Position all transducer lines snug in the joint and tape along outside wall (Dwg. FSE 1074-01). With the internal apparatus in place, butt and strap weld the two end-caps in place using the specified procedures. As soon as the joint has hardened so that the specimen may be moved safely, hoist the specimen carefully with the strap sling into the curing oven. When the specimen has reached its final cure lift the specimen from the oven and replace it on the preparation cradle. Spray test section of laminate or joint with Brittle-Coat, and for FRP laminates, attach four strain transducers, two in each of the principal strain directions. Attach the pressure transducers in their respective ports and connect all instrumentation wires, taping them to the side of the specimen to keep them from tangling or otherwise being damaged. Hoist the specimen in the sling and move it along the overhead rail to a position directly over the test bed. Gently lower the specimen into the water while an assistant slowly fills the inside of the specimen through the use of the bleed valve and the hydraulic hoses. Water from the high-pressure header can be metered into the test model using the manual valve to facilitate the filling process. Attach the pressure and vacuum hoses and the instrumentation wires. As a final precaution, check that all wires are safely out of the way, that all hoses and instrumentation wires are connected correctly, and that the valves on the pressure lines are open and the bleed port closed.

### 7.2.2 Fracture tests

With the test model in the test bath and the pressure hoses connected, check that all valves are open and that the process control and data acquisition systems and off-line data storage are ready. Check the system's integrity by taking each pressure transducer off-line in sequence one at a time. The warning light on the console should illuminate and CRT should indicate a pressure malfunction. These tests shall be conducted with no pressure differential across the laminate wall. Enter a ramp loading strain rate of 0.1 in./in. per minute in the microcomputer and begin the test. At each half second interval store pressure and strain measurements. Calculate modulus of elasticity and Poisson's Ratio. When the "failure" light illuminates, stop the test and secure the system for that test station. Close the manual valve on both pressure lines. Disconnect the hydraulic lines and empty the model. Remove the test model from the bath using the chain hoist and nylon sling. Repeat the test as required.

### 7.2.3. Fatigue tests

With the test models in the test bath and the pressure lines connected, open the pressure and vacuum valves. Check that all data acquisition lines are securely fastened and connected. Perform the systems integrity check as outlined above. Enter the appropriate mean stress RMS level for the test in accordance with Table 1. Check that the system is on-line and operating normally. Begin the tests. At the peak of each cycle store pressure, strain measurements, and cycles. Calculate modulus of elasticity and display. Retain data for 30 minutes. When the "failure" lights illuminate stop the appropriate test and secure the system for that test station. Remove the test model from the bath

### 7.2.4 End-term fracture tests

Perform in accordance with Section 7.2.2 using specimens conditioned as per Section 6.1.

#### 7.2.5 Flexure tests

All flexure tests to be performed as described above except that test load shall be applied to the ends of the test model using hydraulic pistons (Dwg. FSE 1074-03) in lieu of internal pressure. Calculate flexural stress from statics using load cell measurement.

#### 7.2.6 Technical management

The test engineer is reminded that the stress levels outlined in Table 3 are to be considered as advisory in nature. This applies particularly to the lower stress levels where the possibility of long test durations is greater and the possibility of run-outs also greater. The test engineer shall maintain complete records at all times, including working plots of data as outlined in Section 9.0. Adjustments in applied stress levels shall be made at the discretion of the test engineer with the object of obtaining meaningful and cost effective test data. It is incumbent upon the engineer to make himself familiar with the references cited in this management plan, to maintain complete control of the test process at all times, and to adjust the testing procedures as necessity warrants.

### 7.3 Calibrations

Each set of calipers used in the measurement of wall thickness and inside diameter shall be calibrated at the beginning of each work day. Pressure transducers shall be calibrated before and after each test. This shall be done by inserting the pressure transducer at the bottom of a stand pipe of distilled water and measuring the distance from the base of the transducer to the surface of the water with the calipers. That distance times the density of water will be the pressure for purposes of calibrating the pressure transducers. Load cell shall be calibrated using calibrated pressure transducer in hydraulic line and calculation of resultant force in cylinder. Records of all calibrations shall be kept by the test engineer.

#### 7.4 Standards

An approved secondary standard for length shall be available for purposes of calibrating the calipers. The standard for time shall be the time signal from radio station WWV in Fort Collins, Colorado.

#### 7.5 Loading Conditions

The Cold Water Pipe is subjected to loads acting concurrently in the three translational and the three rotational directions. For the purposes of this test program, the chief principal strains to be investigated shall be the axial strain and hoop strain in the test cylinder. For the fracture test series these strains shall be induced through the application of pressure in the end-caps such that a constant strain rate of 0.1 in./in. per minute is maintained until the test specimen ruptures. For the fatigue tests a non-stationary random load signal shall be produced by the micro-computer. This random load shall have specified statistical parameters as provided by NOAA, which shall include: fundamental frequency of oscillation of the pipe/hull structure and the standard deviation of the normal distribution of root mean square load levels as shown in Figure 1.

#### 7.6 Failure Criteria

The failure criteria used by Reifsnieder, Stinchcomb, and O'Brien (7) is endorsed for the fatigue tests in this test program. In this study, stiffness change is used as the primary damage parameter, and a reduction in stiffness of 18% is used as a failure criterion. Care must be exercised by the test engineer in distinguishing a true reduction in stiffness as opposed to an apparent loss of stiffness due to transient errors in measurement. The same criteria applies to joint failure in which case the axial strain transducer shall be positioned across the interior joint and either loss of stiffness or joint shear will indicate failure. All fracture tests shall be taken to complete rupture of the test model.

## 8.0 DATA ANALYSIS

The analysis of experimental data involves consideration of three general concerns. The first is the accuracy of the measurements and the propagation of error in computed results. The accuracy of a measurement is affected by systematic errors, such as: errors of calibration, personal errors, experimental conditions, and imperfect technique. The second is a consideration of the precision of the measured data as expressed by its statistical distribution. The precision of a measurement is affected by random errors such as: errors of judgement, fluctuating conditions, small disturbances, or an error of definition. And the third is a determination of the general validity of the experimental measurements and a rational criteria for the rejection of suspicious data. The general validity of experimental data, moreover, depends on the accuracy of the measurements and the precision with which those measurements are made.

The engineer shall exercise all possible care to avoid systematic errors. Rigorous calibration of the instruments shall be maintained as well as strict control of the testing process. He shall use his total laboratory experience to insure that errors in the test do not exceed the specified maximum allowable error at the specified level of confidence required. Both the cost of the test and the duration of the test are directly affected by these two criteria.

### 8.1 Error Analysis

The failure criterion which governs the testing process is the loss of stiffness, or modulus of elasticity, in the test model. The modulus of elasticity, however, is not a directly measureable quantity. It is derived from elastic theory as a function of the measured quantities of pressure, strain, and model geometry.

Considering a filament wound FRP pipe wall to be a linear elastic, isotropic material in the hoop and axial directions, Hooke's law can be applied (1):

$$E_x = \frac{\sigma_x - \nu(\sigma_y + \sigma_z)}{\epsilon_x} \quad (1)$$

### 8.1 Error Analysis (continued)

Where:

$\sigma_{x,y,z}$  = stress, psi

$\epsilon_{x,y}$  = strain, in./in.

$\nu$  = Poisson's Ratio,  
(from initial fracture tests)

Utilizing the tangent modulus of elasticity, Equation (1) becomes:

$$E_t = \frac{|\sigma_{x_2} - \nu(\sigma_{y_2})| - |\sigma_{x_1} - \nu(\sigma_{y_1})|}{|\epsilon_{x_2} - \epsilon_{x_1}|} \quad (2)$$

Where:

$\sigma_{x_1} = \sigma_{x_1}(P_1, i, t)$  Time 1

$\sigma_{x_2} = \sigma_{x_2}(P_2, i, t)$  Time 2

$\sigma_{y_1} = \sigma_{y_1}(\Delta P_1, i, t)$  Time 1

$\sigma_{y_2} = \sigma_{y_2}(\Delta P_2, i, t)$  Time 2

$\epsilon_1$  = Strain at Time 1

$\epsilon_2$  = Strain at Time 2

Not only are measured quantities subject to random and systematic errors, the calculation of results using measured quantities are also subject to the propagation of these errors in the calculations. Thus, errors associated with the measurement of pressure, strain, and model geometry will affect the accuracy of the final computed modulus of elasticity.

### 8.1 Error Analysis (continued)

Using the methods of Kline and McKlintock (4), given:

$$E_t = E_t (P_1, P_2, \Delta P_1, \Delta P_2, \epsilon_{x1}, \epsilon_{x2}, i, t) \quad (3)$$

Where:  $E_t$  = Tangent Modulus of Elasticity, psi

$P_{1,2}$  = Pressure in end-caps at Times 1 and 2, psi

$\Delta P_{1,2}$  = Differential Pressure in Midsection at Times 1 and 2

$\epsilon_{x1,2}$  = Axial strains at Times 1 and 2

$\epsilon_{y1,2}$  = Hoop strains at Times 1 and 2

$i$  = Mean Inside Diameter, inches

$t$  = Mean Wall Thickness, inches

The uncertainty in  $E_t$  (the level of confidence for all factors presumed equal) can then be expressed:

$$\omega_{E_t} = \left[ \left( \frac{\partial E_t}{\partial P_1} \omega_{P_1} \right)^2 + \left( \frac{\partial E_t}{\partial P_2} \omega_{P_2} \right)^2 + \dots + \left( \frac{\partial E_t}{\partial t} \omega_t \right)^2 \right]^{1/2} \quad (4)$$

### 8.1 Error Analysis (continued)

Where:  $w_{E_E}$  = Uncertainty in the calculated result

$w_n$  = Uncertainty in the independent variable

Note: Refer to Appendix 13.2 for the derivation of the final uncertainty in the computed tangent modulus of elasticity.

The test engineer is cautioned to pay particular notice to the squares of the uncertainties in the independent variables  $w_n$ . Should the uncertainty in one variable be significantly larger than the uncertainties in the other variables, say by a factor of 5 or 10, then attention should be paid to this factor and the possible causes for its predominance determined and eliminated if possible.

### 8.2 Statistical Analysis

The methods of statistical analysis are used throughout the test program in controlling the test processes, assuring that the data taken and the results obtained are meaningful with a consistent reliability, providing a rational basis for correlating the effects of scalability with real conditions, and in optimizing the test processes to obtain the most cost-effective test program possible in terms of time and money.

Taking advantage of the high speed of modern microcomputers, numerous measurements of pressure and strain can be made at small intervals in time. These sets of measurements can be analyzed statistically for the arithmetic mean and standard deviation and these quantities used in the calculation of the modulus of elasticity.

An important application of statistical methods in the test program involves determination of sample size. Following each test in a series, the arithmetic mean and standard deviation of the results of the test series

## 8.2 Statistical Analysis (continued)

to that point shall be computed and the procedure outlined in Appendix 13.3 used to determine if the statistical requirements of the program have been met. If the computed sample size is less than the number of tests which have been run in that series, the statistical requirements have been met and the series can be terminated. If the sample size is larger, however, another test must be run and the same calculation repeated. Before terminating a test series, however, Chauvenet's criteria for the rejection of suspicious data should be applied to the test data and any data not meeting its requirements rejected (Table 2). Another calculation of the sample size may then be necessary.

The final application of statistical methods in the testing program involves calculation and construction of probability curves for the final test results. As an example, the results of a fatigue test are plotted on graph paper and the strength distribution at a service life of 30 years is determined. In the particular case of fatigue testing, the distribution corresponds to a Three Parameter Weibull distribution (3,7) and using the methods of statistical analysis the probabilities of different levels of strengths can be computed. Hence, the final results of the testing program, i.e. a set of design stresses for a FRP Cold Water Pipe, can be formulated based upon realistic and meaningful probabilities.

## 9.0 DOCUMENTATION OF RESULTS

### 9.1 Fracture Data

A traditional normal plot of stress versus strain and a least-squares fit of the series data should be plotted identifying the points listed in Figure 3. In addition, plots of stress, strain, and rate of strain versus the dynamic tangent modulus and Poisson's Ratio should also be made.

### 9.2 Fatigue Data

Fatigue-life data are plotted on conventional S-N diagrams. Here, it is assumed that to each specimen of the population can be attributed an individual S-N curve, and that there exists for any population of specimens (at fixed test conditions) a family of nonintersecting S-N curves, which can be determined with any desired accuracy, each curve corresponding to a given probability (8).

The average S-N curve is then fitted to all the test points on the S-N diagram by using the least-squares method. Passing through each test point, an S-N curve parallel to the average S-N curve is drawn. These will make a family of S-N curves. (See Figure 4). For a strength distribution at a service life of 30 years, a vertical line is drawn at  $N = 30$  years intersecting the family of S-N curves. These points of intersection  $S_1, S_2, \dots$  represent a sample from the strength distribution at that life. These data are then plotted on several probability papers as a cumulative distribution function to determine the strength distribution. (See Figure 6). Weibull distribution has been found to fit the fatigue-strength data well (9).

In a similar manner, the scatter in the fatigue strength at  $N = 30$  years can be obtained for various values of  $P$ , where  $P$  is the fraction of the total specimens that have the fatigue strength of at least  $S_a$  (3).

### 9.3 Flexure Data

Data obtained from both fracture and fatigue flexure tests shall be plotted using the same methods as with their respective tests described above (Figure 7).

#### 9.4 Acoustic Emissions Data

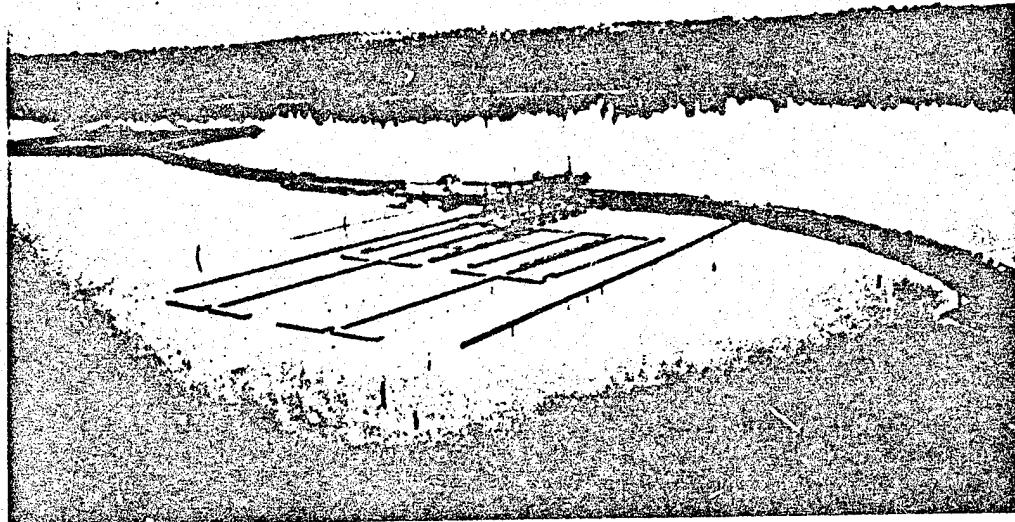
One of the major attractions of acoustic emissions monitoring is the basic simplicity of the technique. As a crack develops in a Fiber Reinforced Plastic laminate the first fracture occurs in the resin matrix. This is followed by cracking of the glass fibers. This cracking produces snaps which are clearly audible to a nearby listener. By attaching acoustic emission transducers to a Fiber Reinforced Plastic laminate which is being strained these snaps can be recorded as they occur. As common sense would indicate, the louder the snaps become and the greater the number of snaps counted, the nearer the laminate is to failure. This has been substantiated by recent research. As Fowler (12) has stated, "acoustic emission provides a reliable indication of creep in FRP materials and a time plot can be used to determine if the creep deformation is becoming unstable, as would occur at failure".

Acoustic emission monitoring has been shown to be an effective tool in materials testing, including fracture, fatigue, and creep tests. Acoustic emission monitoring has also been shown to be an effective method of detection and location of flaw growth in composite structures and in prediction of structural failures (14, 15). Figures 8, 9, and 10 show typical graphical representations of acoustic emission data for tensile fracture and fatigue tests.

#### 9.5 Photographic Documentation

All specimens will be photographed following removal from bath. Strain fields, as delineated by brittle coat cracking, shall be darkened with grease pencil for contrast in photography.

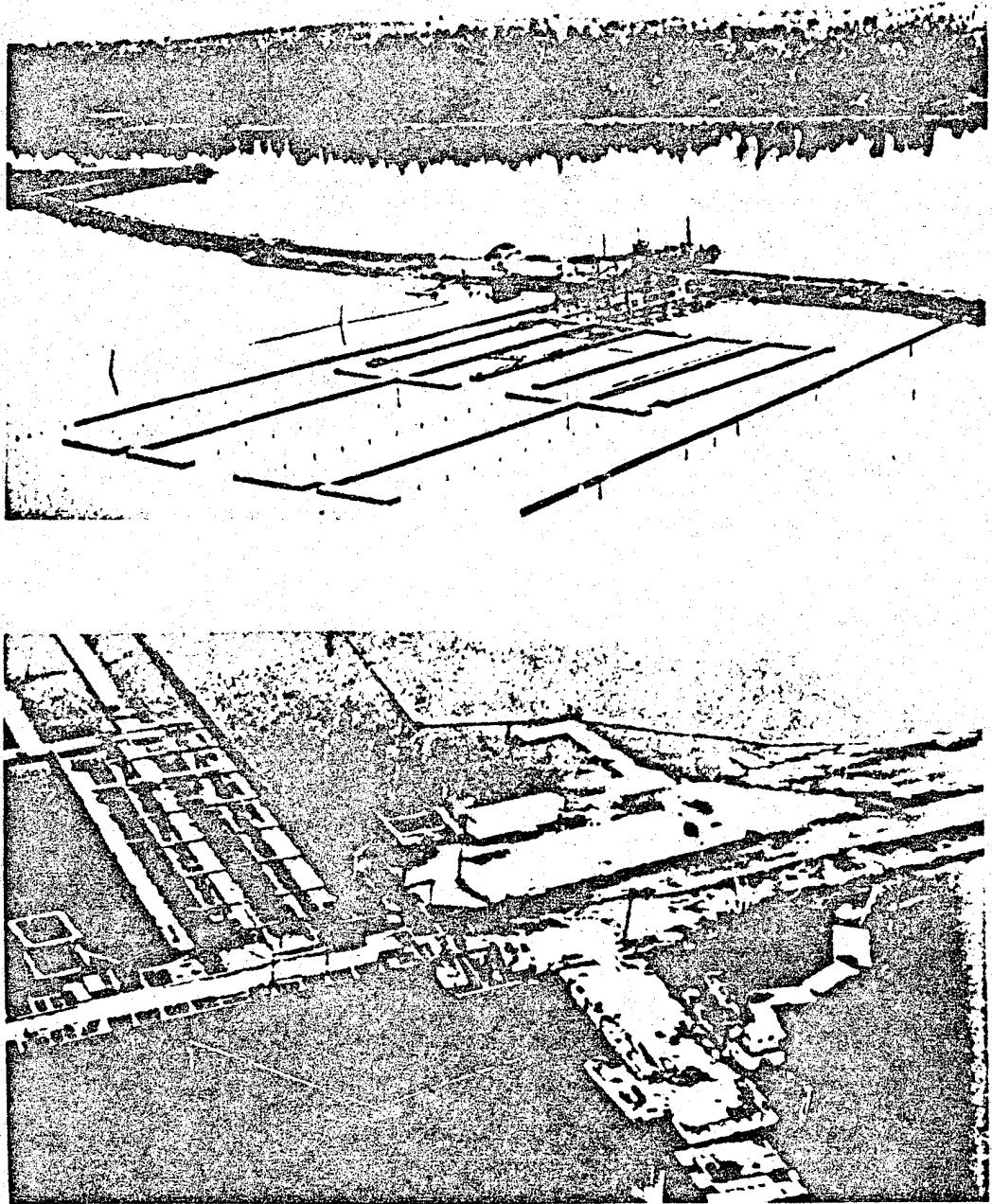
## 10.0 POTENTIAL TEST SITES



Lummi Aquiculture Site  
Bellingham, Washington

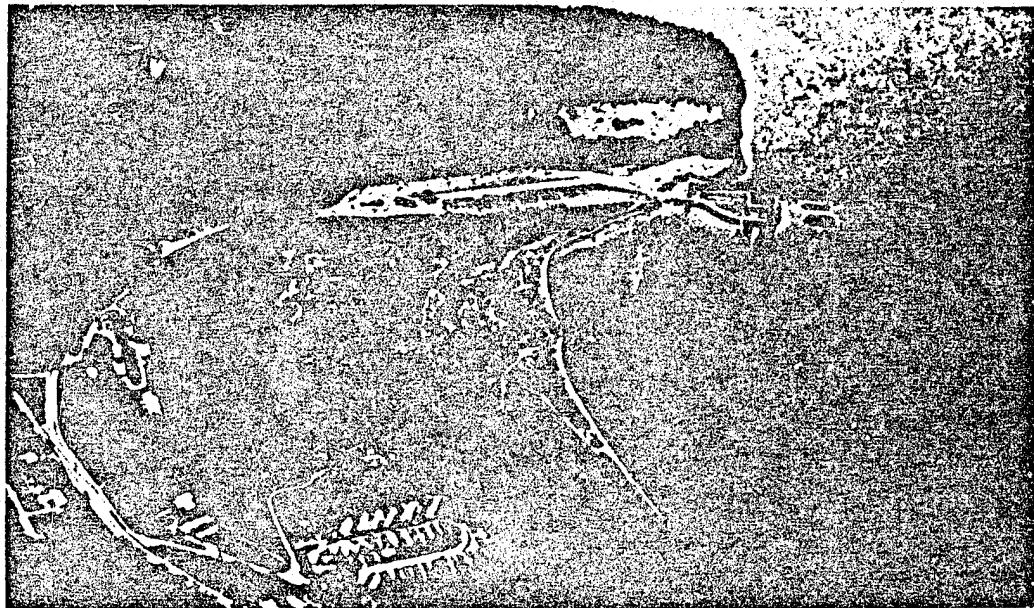
The Lummi Aquiculture Center is a system of tidal pools used as part of a salmon hatchery and oyster farming program. Several pools, covering several hundred acres, comprise the tidal facilities of the Lummi Aquiculture program. An unused portion of one of these tidal pools has been located in which the testing program could be conducted with a minimum expenditure in facilities buildup. Space for the various testing equipment is available adjacent to one of the tidal ponds. Both 110 volts and 220 volt electrical power is available at the site with a circuit rating on the 220 volt circuit of 50 amperes. An existing overhead rail is also available (Drawing FSE 1074-03). The Lummi Aquiculture Center is located on the Lummi Indian reservation north of Bellingham, Washington and is operated by the Lummi Indian Tribal Council. Initial inquiries indicate that use of the existing facilities would be acceptable to the Tribal Council, although before final authorization is given a formal letter of request should be submitted for Council approval.

## 10.0 POTENTIAL TEST SITES



Lummi Aquiculture Site  
Bellingham, Washington

## 10.0 POTENTIAL TEST SITES



Shannon Point Marine Laboratory  
Anacortes, Washington

## **11.0 COSTS**

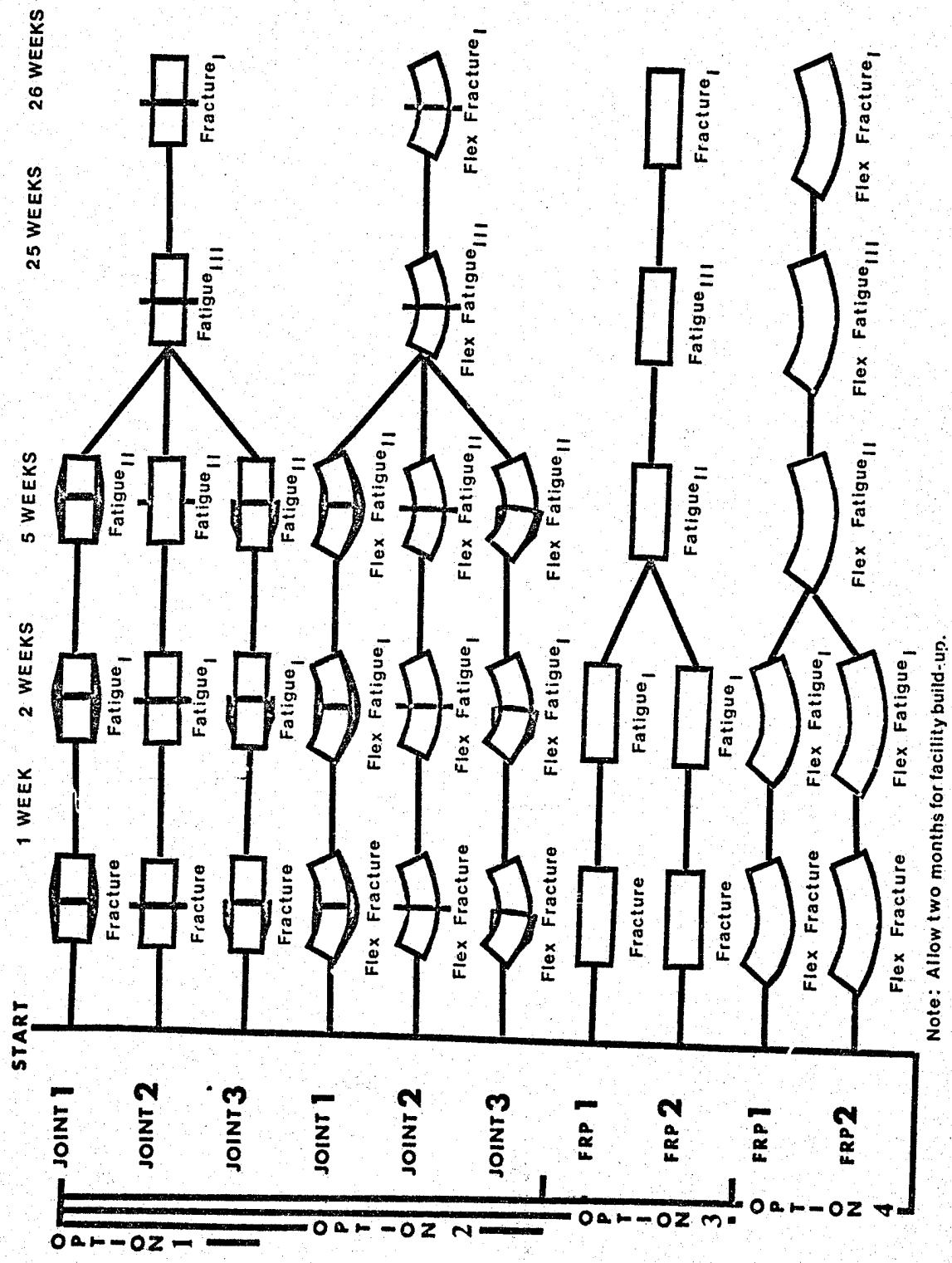
## 11.0 COSTS

	OPTIONS			
	1	2	3	4
<u>Facility</u>				
Bath		Lease	Negotiable	
Hydraulics	6,000	6,000	6,000	6,000
Construction	500	500	500	500
Trailer Rental	1,425	1,425	1,425	1,425
	\$ 7,925	\$ 7,925	\$ 7,925	\$ 7,925
<u>Process Control</u>				
Microcomputer	15,000	15,000	15,000	15,000
Control Panel	350	350	350	350
I/O Interface	3,800	3,800	3,800	3,800
Software	3,500	3,500	3,500	3,500
	\$ 22,650	\$ 22,650	\$ 22,650	\$ 22,650
<u>Data Acquisition</u>				
Strain Transducers	2,000	4,000	5,000	6,000
Pressure Transducers	1,500	1,500	1,500	1,500
	\$ 3,500	\$ 5,500	\$ 6,500	\$ 7,500
<u>Test Models 20"Ø</u>				
FRP Pipe	-0-	-0-	2,351	-0-
Flanged Joints	26,738	50,106	50,106	50,106
Butt & Strap Joints	7,981	15,962	15,962	15,962
End Caps	4,316	8,132	10,676	13,220
Attach Caps	38,500	77,000	96,250	115,500
Steel Internals	3,642	7,284	9,712	12,140
	\$ 81,177	\$158,484	\$185,057	\$211,553
<u>Test Personnel</u>				
Test Engineer	36,397	36,397	36,397	36,397
Technician	10,399	10,399	10,399	10,399
	\$ 46,796	\$ 46,796	\$ 46,796	\$ 46,796
<b>TOTALS</b>	<b>\$162,048</b>	<b>\$241,355</b>	<b>\$268,928</b>	<b>\$291,799</b>

Optional Acoustic Emission Data Acquisition System - \$10,000.

## **12.0 SCHEDULES**

## TEST SCHEDULE



## COST SCHEDULE

OPTION 4

OPTION 2

OPTION 3

OPTION 1

### TEST FACILITY

#### Bath - negotiable -

Hydraulics \$6,000

Construction \$500

Trailer Rental \$1,450

### PROCESS CONTROL

#### Microcomputer

Control Panel \$350

I/O Interface \$3,800

Software \$3,500

### DATA ACQUISITION

Strain Transducers \$2,000

Pressure Transducers 1,500

### TEST MODELS - 20" Q

#### FRP Pipe

#### Flanged Joints

Bolt & Strap Joints \$7,981

End Caps \$1,316

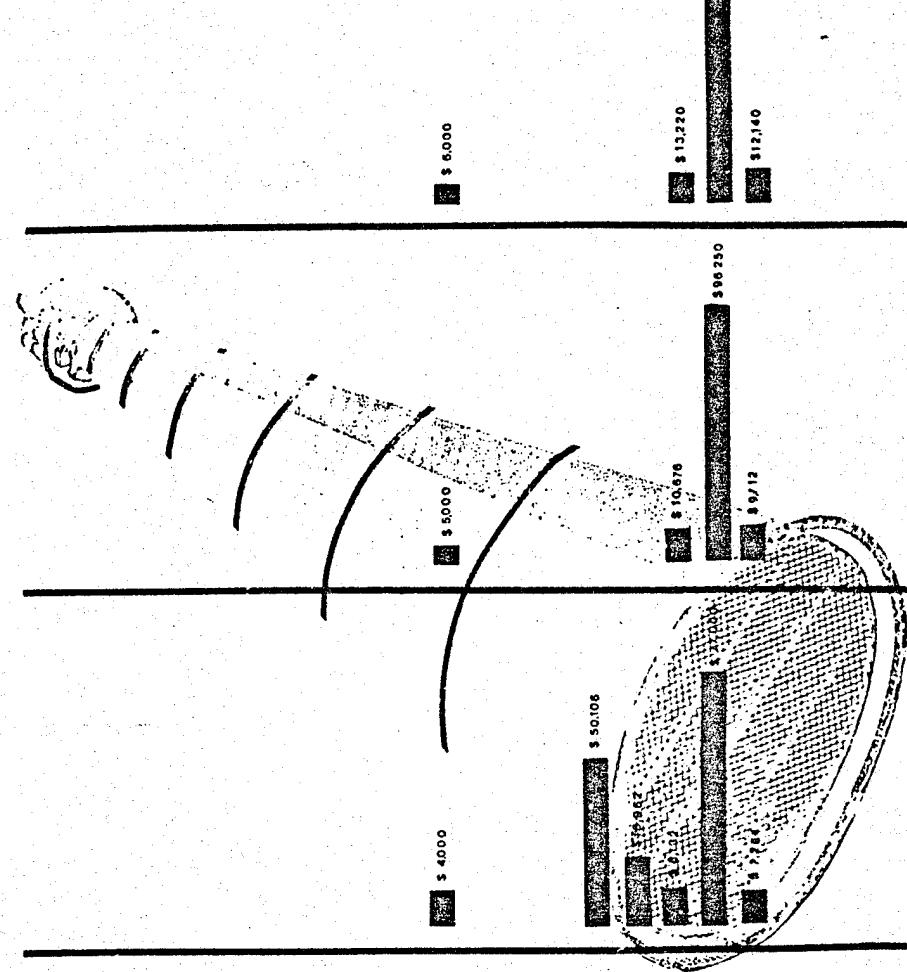
Attach Caps \$30,500

Steel Internals \$3,862

### TEST PERSONNEL

Test Engineer \$36,397

Technician \$10,399



### **13.0 APPENDIX**

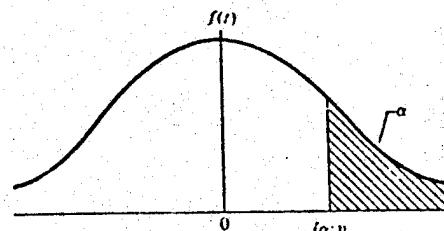
### **13.1 Tables**

<u>Option</u>	<u>Test</u>	<u>Loading Sequence</u>	<u>Results</u>
1	Joint Fracture	Load to Rupture Strain Rate 0.1/min.	$\sigma_f$ E
	Joint Fatigue	I S= 0.75 $\sigma_f$ II S= 0.60 $\sigma_f$ III S= 0.40 $\sigma_f$	N, cycles to failure
2	Joint Flexure Fracture	Load to Rupture, Strain Rate 0.1/min.	$\sigma_{flex}$ E
	Joint Flexure Fatigue	I S= 0.75 $\sigma_{flex}$ II S= 0.60 $\sigma_{flex}$ III S= 0.40 $\sigma_{flex}$	N, cycles to failure
3	FRP Fracture	Load to Rupture Strain Rate, 0.1/min.	$\sigma_f$ E v
	FRP Fatigue	I S= 0.75 $\sigma_f$ II S= 0.60 $\sigma_f$ III S= 0.40 $\sigma_f$	N, cycles to failure
4	FRP Flexure Fracture	Load to Rupture Strain Rate 0.1/min.	$\sigma_{flex}$ E
	FRP Flexure Fatigue	I S= 0.75 $\sigma_{flex}$ II S= 0.60 $\sigma_{flex}$ III S= 0.40 $\sigma_{flex}$	N, cycles to failure

TABLE 1

## t Distribution

Table 2



$v$	$\alpha$	.40	.30	.20	.10	.050	.025	.010	.005	.001	.0005
1		.325	.727	1.376	3.078	6.314	12.71	31.82	63.66	318.3	636.6
2		.289	.617	1.061	1.886	2.920	4.303	6.965	9.925	22.33	31.60
3		.277	.584	.978	1.638	2.353	3.182	4.541	5.841	10.22	12.94
4		.271	.569	.941	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5		.267	.559	.920	1.476	2.015	2.571	3.365	4.032	5.893	6.859
6		.265	.553	.906	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7		.263	.549	.896	1.415	1.895	2.365	2.998	3.499	4.785	5.405
8		.262	.546	.889	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9		.261	.543	.883	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10		.260	.542	.879	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11		.260	.540	.876	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12		.259	.539	.873	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13		.259	.538	.870	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14		.258	.537	.868	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15		.258	.536	.866	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16		.258	.535	.865	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17		.257	.534	.863	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18		.257	.534	.862	1.330	1.734	2.101	2.552	2.878	3.611	3.922
19		.257	.533	.861	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20		.257	.533	.860	1.325	1.725	2.086	2.528	2.845	3.552	3.800
21		.257	.532	.859	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22		.256	.532	.858	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23		.256	.532	.858	1.319	1.714	2.069	2.500	2.807	3.485	3.767
24		.256	.531	.857	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25		.256	.531	.856	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26		.256	.531	.856	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27		.256	.531	.855	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28		.256	.530	.855	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29		.256	.530	.854	1.311	1.699	2.045	2.462	2.756	3.393	3.659
30		.256	.530	.854	1.310	1.697	2.042	2.457	2.750	3.383	3.646
40		.255	.529	.851	1.303	1.694	2.021	2.423	2.704	3.307	3.551
50		.255	.528	.849	1.298	1.676	2.009	2.403	2.678	3.262	3.495
60		.254	.527	.848	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80		.254	.527	.846	1.292	1.664	1.990	2.374	2.639	3.195	3.415
100		.254	.526	.845	1.290	1.660	1.984	2.365	2.626	3.174	3.389
200		.254	.525	.843	1.286	1.653	1.972	2.345	2.601	3.131	3.339
500		.253	.525	.842	1.283	1.648	1.965	2.334	2.586	3.106	3.310
$\infty$		.253	.524	.842	1.282	1.645	1.960	2.326	2.576	3.090	3.291

\* Tabulation of the values of  $\alpha$  versus  $t_{\alpha/2, v}$  for different values of  $v$ .

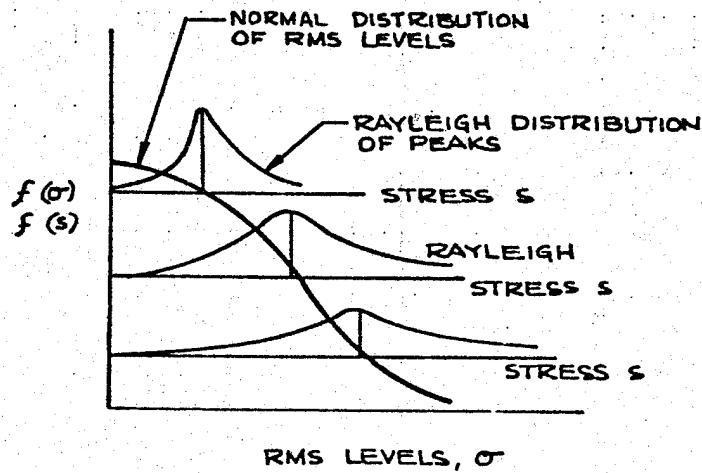
$$\alpha = P(t > t_{\alpha/2, v}) = \int_{t_{\alpha/2, v}}^{\infty} f(t) dt$$

Chauvenet's Criterion for the  
Rejection of Suspicious Data Points

Number of readings,	Ratio of maximum acceptable deviation to standard deviation
n	$\frac{d_{\max}}{\sigma}$
2	1.15
3	1.38
4	1.54
5	1.65
6	1.73
7	1.80
10	1.96
15	2.13
25	2.33
50	2.57
100	2.81

TABLE 3

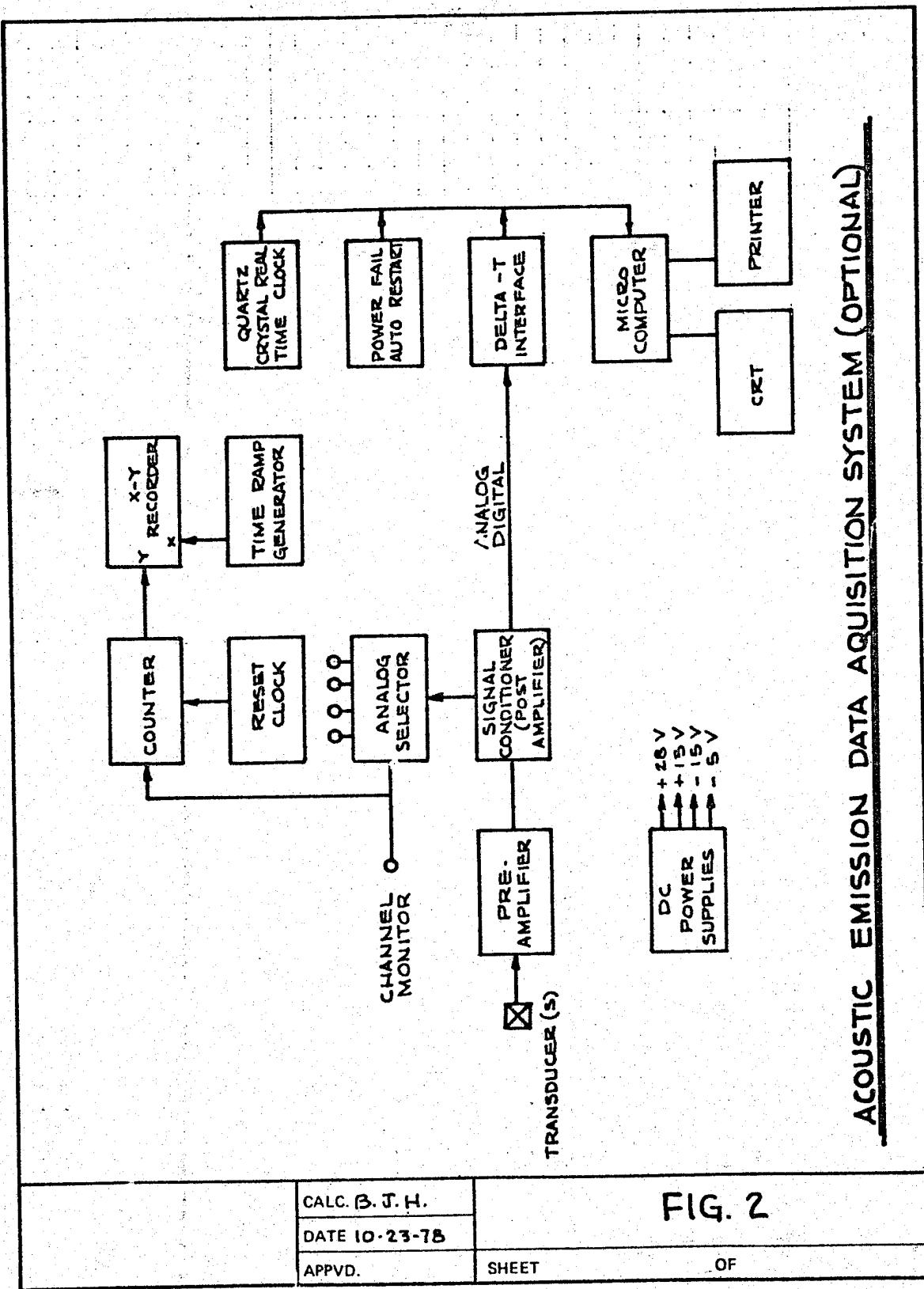
## 13.2 Figures

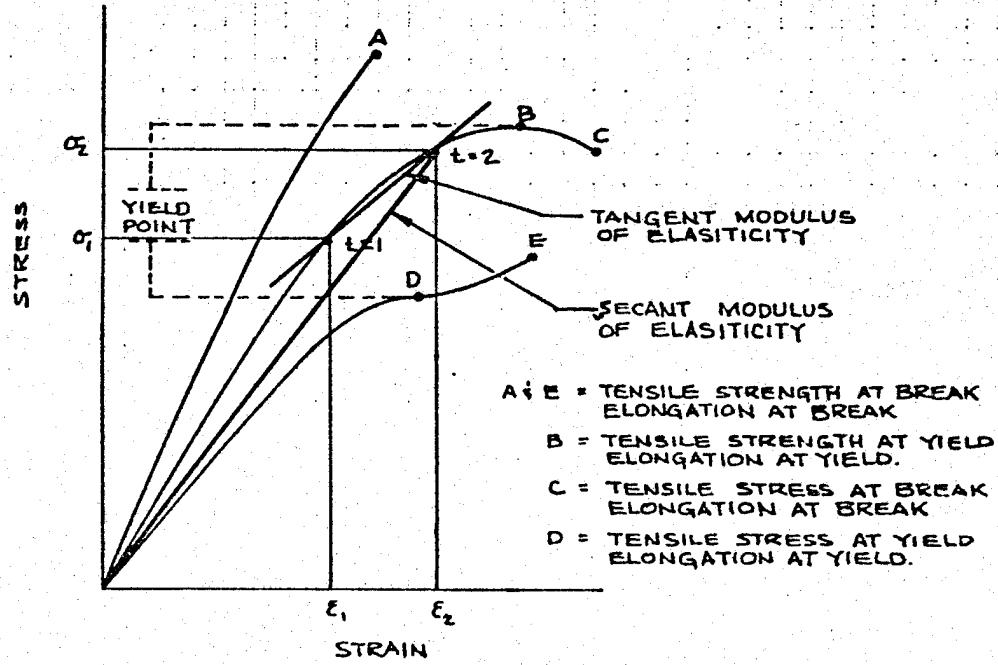


### RANDOM LOAD CONTROL SYSTEM

REF: [3] LIPSON, C. AND SHETH, N.J., "STATISTICAL DESIGN AND ANALYSIS OF ENGINEERING EXPERIMENTS", McGRAW-HILL, 1973

	CALC. B. J. H.	FIG. 1
	DATE 10-23-78	
	APPVD.	SHEET OF

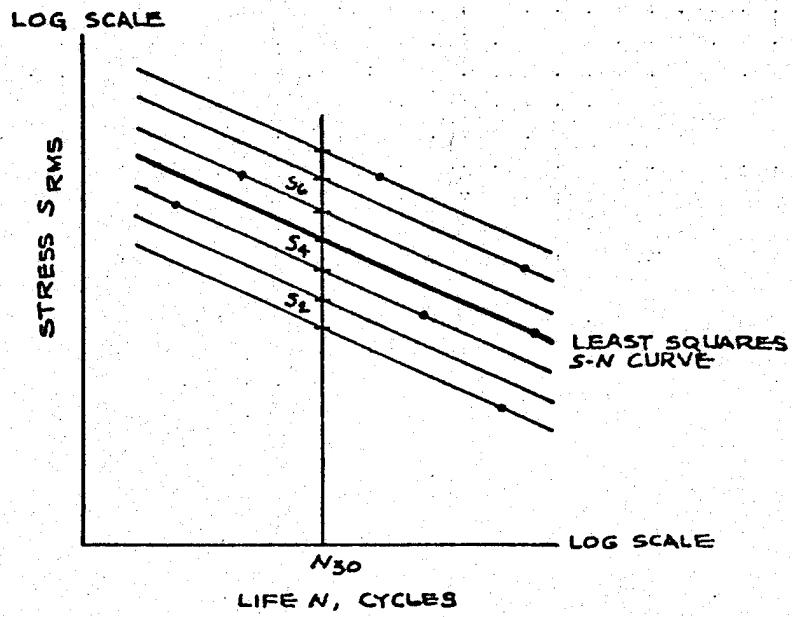




### TENSILE DESIGNATIONS

REF: [13] "STANDARD TEST METHOD FOR TENSILE PROPERTIES OF PLASTICS", 1977 ANNUAL BOOK OF ASTM STANDARDS, PART 35, PG. 215.

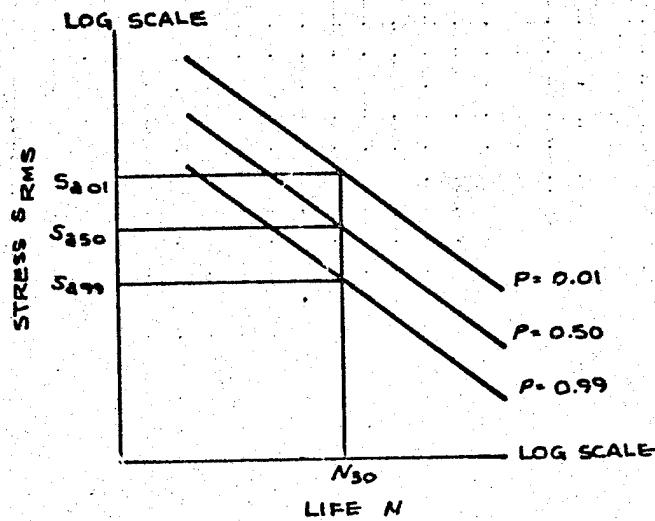
	CALC. B.J. H.	FIG. 3	
	DATE 9-24-78		
APPVD.	SHEET	OF	



S-N DIAGRAM FOR CONVERTING LIFE DATA  
TO STRENGTH DATA

REF: [3] LIPSON, C., AND SHETH, N.J., "STATISTICAL DESIGN AND ANALYSIS OF ENGINEERING EXPERIMENTS", McGRAW-HILL, 1973

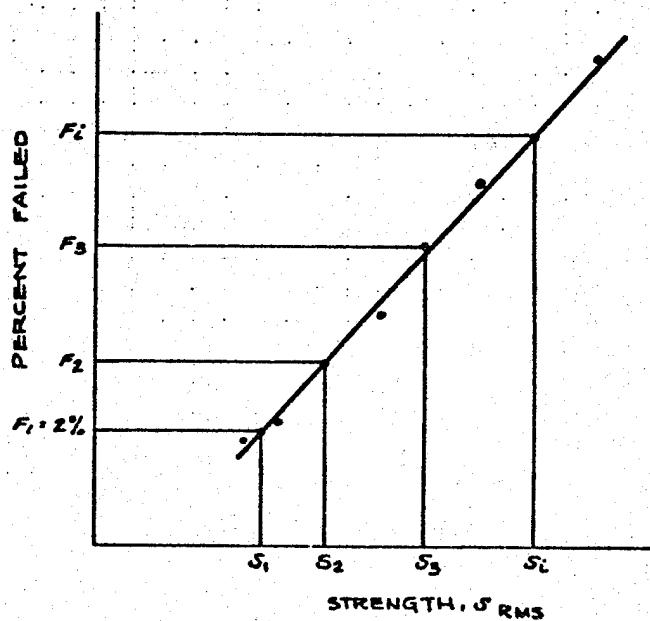
CALC. B.J.H.		FIG. 4	
DATE 9-24-78			
APPVD.	SHEET	OF	



P-S-N CURVES ILLUSTRATING THE SCATTER IN FATIGUE  
STRENGTH AT A GIVEN LIFE

REF: [3] LIPSON, C., AND SHETH, N.J., "STATISTICAL DESIGN AND ANALYSIS OF ENGINEERING EXPERIMENTS", McGRAW-HILL, 1973.

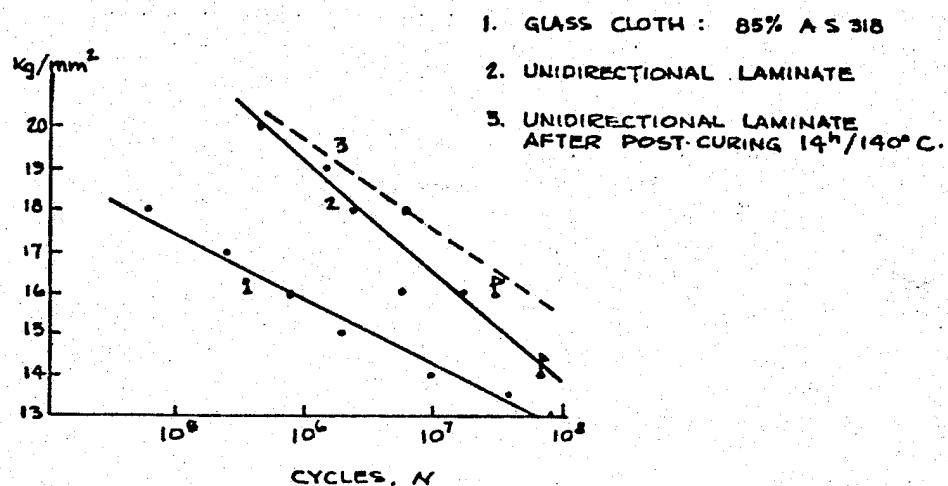
	CALC. B.J.H.	FIG. 5	
	DATE 9-27-78		
	APPVD.	SHEET	OF



PLOT OF STRENGTH RESPONSE DATA  
ON PROBABILITY PAPER

REF: [3] LIPSON, C. AND SHETH, H.J., "STATISTICAL DESIGN AND ANALYSIS OF ENGINEERING EXPERIMENTS", MCGRAW-HILL, 1973

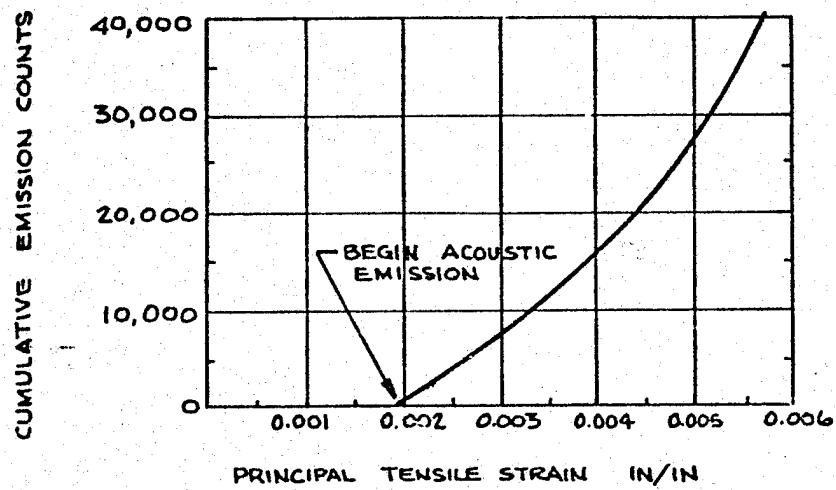
CALC. B.J.H.	FIG. 6	
DATE 9-24-78		
APVVD.	SHEET	OF



### DYNAMIC FLEXURAL TEST

REF: [10] FINDLEY, W. N., "PREDICTIONS OF PERFORMANCE OF PLASTICS UNDER LONG-TERM STATIC LOADS", JUNE 1962.

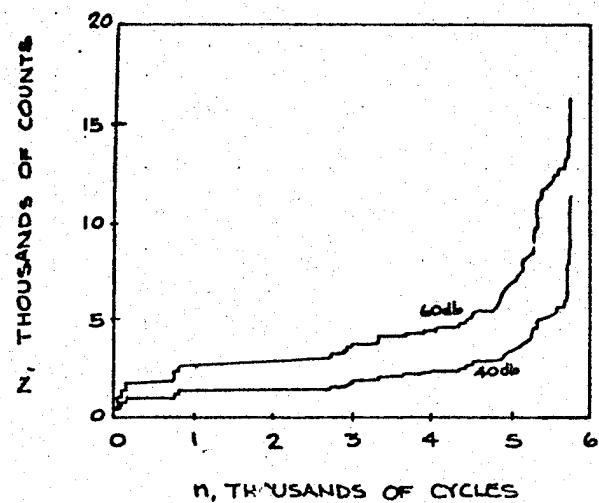
	CALC. B. J. H.	FIG. 7
	DATE 9-24-78	
	APPVD.	SHEET OF



### TENSILE ACOUSTIC EMISSION (100-300 KHz)

REF: [2] FOWLER, TIMOTHY J., "ACOUSTIC EMISSION TESTING OF FIBER REINFORCED PLASTICS", PAPER PRESENTED AT ASCE FALL CONVENTION, OCTOBER 17-21, 1977, PREPRINT 3092

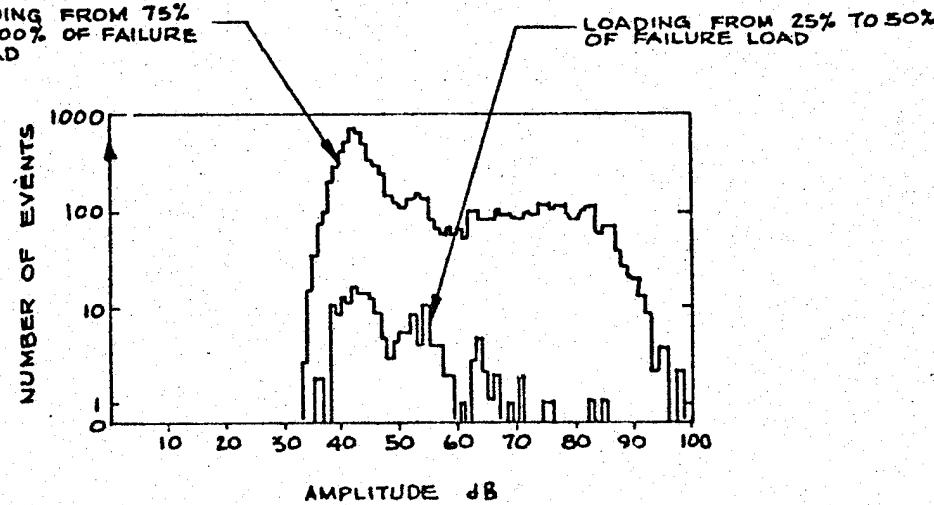
	CALC. B.J.H	FIG. 8	
	DATE 10-24-78		
	APPVD.	SHEET	OF



SUMMATION OF ACOUSTIC EMISSION COUNTS AS A  
FUNCTION OF THE NUMBER OF FATIGUE CYCLES

REF: [15] DUNEGAN, H.L., "USING ACOUSTIC EMISSION TECHNOLOGY TO PREDICT STRUCTURAL FAILURE", METALS ENGINEERING QUARTERLY, FEBRUARY 1975.

	CALC. B.J.H.	FIG. 9
	DATE 9-24-78	
	APPVD.	SHEET OF



ACOUSTIC EMISSION AMPLITUDE DISTRIBUTION  
FOR DIFFERENT LOADING RANGES

REF: [12] FOWLER, TIMOTHY J., "ACOUSTIC EMISSION TESTING OF FIBER REINFORCED PLASTICS", PAPER PRESENTED AT ASCE FALL CONVENTION, OCTOBER 17-21, 1977, PREPRINT 3092.

CALC. B.J.H.	
DATE 9-24-78	
APPVD.	SHEET . OF

FIG. 10

### 13.3 Calculations

### 13.3 Calculations

#### Process Control Integrity Checks

$$|P_1 - P_2|_{RMS} \leq k_1 \left( \frac{P_1 + P_2}{2} \right) \quad (a)$$

$$|\varepsilon_{x_1} - \varepsilon_{x_2}|_{RMS} \leq k_2 \left( \frac{\varepsilon_{x_1} + \varepsilon_{x_2}}{2} \right) \quad (b)$$

$$|\varepsilon_{y_1} - \varepsilon_{y_2}|_{RMS} \leq k_3 \left( \frac{\varepsilon_{y_1} + \varepsilon_{y_2}}{2} \right) \quad (c)$$

$$|P_{v1} - P_{v2}|_{RMS} \leq k_4 \left( \frac{P_{v1} + P_{v2}}{2} \right) \quad (d)$$

$$\left| \frac{W_{E_t}}{E_t} \right|_{RMS} \leq k_5 \quad (e)$$

#### Failure Checks

$$E_t \leq k_6 E_0 \quad (f)$$

$$\frac{E_{t_2} - E_{t_1}}{t_2 - t_1} \geq k_7 \quad (g)$$

where:  $k_n$  = Maximum Errors  
 $k_6$  = Failure Stiffness  
 $k_7$  = Stiffness Loss  
 Rate at Failure,  
 psi/sec

$P_n$  = Pressures, psi  
 $\varepsilon_n$  = Strains, in/in  
 $E_t$  = Tangent Modulus, psi  
 $W_{E_t}$  = Modulus Uncertainty,  
 psi

### Error Analysis

Hooke's Law

$$E = \frac{\sigma}{\epsilon} \quad (h)$$

Where:

$$\sigma = \sigma_x - \nu(\sigma_y + \sigma_z)$$

$$\epsilon = \epsilon_x$$

$$\nu = \frac{\epsilon_y}{\epsilon_x} \quad (\text{From Fracture Test})$$

### Tangent Modulus of Elasticity

$$E_t = \frac{|\sigma_z - \sigma_i|}{|\epsilon_z - \epsilon_i|} \quad (i)$$

$$= \frac{|[\sigma_{x_2} - \nu \sigma_{y_2}] - [\sigma_{x_1} - \nu \sigma_{y_1}]|}{|\epsilon_{x_2} - \epsilon_{x_1}|}$$

Where:

$$\sigma_y = \frac{\Delta P}{2t}$$

$$\sigma_x = \frac{P_i}{\pi t (i+t)}$$

$P$  = Pressure in End-Cap

$\Delta P$  = Pressure Differential across Test Model

$i$  = Mean Inside Diameter

$t$  = Mean Wall Thickness

Error Analysis (continued)

$$E_t = \frac{\left| \left[ \frac{P_{2,i}}{\pi t(i+t)} - \nu \left( \frac{\Delta P_{2,i}}{2t} \right) \right] - \left[ \frac{P_{1,i}}{\pi t(i+t)} - \nu \left( \frac{\Delta P_{1,i}}{2t} \right) \right] \right|}{|\varepsilon_2 - \varepsilon_1|} \quad (j)$$

From Kline and McClintock (4):

$$w_{Et} = \left[ \left( \frac{\partial E_t}{\partial P_1} w_{P_1} \right)^2 + \left( \frac{\partial E_t}{\partial P_2} w_{P_2} \right)^2 + \dots + \left( \frac{\partial E_t}{\partial \varepsilon} w_{\varepsilon} \right)^2 \right]^{1/2} \quad (k)$$

Where:

$$\frac{\partial E_t}{\partial P_1} = [\varepsilon_2 - \varepsilon_1]^{-1} \left[ \frac{-i}{\pi t(i+t)} \right]$$

$$\frac{\partial E_t}{\partial P_2} = [\varepsilon_2 - \varepsilon_1]^{-1} \left[ \frac{i}{\pi t(i+t)} \right]$$

$$\frac{\partial E_t}{\partial \Delta P_1} = [\varepsilon_2 - \varepsilon_1]^{-1} \left[ \frac{\nu i}{2t} \right]$$

$$\frac{\partial E_t}{\partial \Delta P_2} = [\varepsilon_2 - \varepsilon_1]^{-1} \left[ \frac{-\nu i}{2t} \right]$$

$$\frac{\partial E_t}{\partial \varepsilon_1} = \left[ \frac{\varepsilon_1}{(\varepsilon_2 - \varepsilon_1)^2} \right] \left[ (P_2 - P_1) \left( \frac{i}{\pi t(i+t)} \right) - (\Delta P_2 - \Delta P_1) \left( \frac{\nu i}{2t} \right) \right]$$

$$\frac{\partial E_t}{\partial \varepsilon_2} = \left[ \frac{\varepsilon_2}{(\varepsilon_2 - \varepsilon_1)^2} \right] \left[ (P_2 - P_1) \left( \frac{i}{\pi t(i+t)} \right) - (\Delta P_2 - \Delta P_1) \left( \frac{\nu i}{2t} \right) \right]$$

Error Analysis (continued)

$$\frac{\partial E_t}{\partial i} = [\varepsilon_2 - \varepsilon_1]^{-1} \left\{ \left[ \frac{\pi t(i+t)P_2 - P_1 i \pi t}{(\pi t(i+t))^2} - \frac{\Delta P_2}{2t} \right] \right. \\ \left. - \left[ \frac{\pi t(i+t)(P_1) - P_2 i \pi t}{(\pi t(i+t))^2} - \frac{\Delta P_1}{2t} \right] \right\}$$

$$\frac{\partial E_t}{\partial t} = [\varepsilon_2 - \varepsilon_1]^{-1} \left\{ [P_1 - P_2] \left[ \frac{\pi(i+2t)}{(\pi i t + \pi t^2)^2} \right] \right. \\ \left. - [\Delta P_1 - \Delta P_2] \left[ \frac{i \nu}{2t^2} \right] \right\}$$

and:

$w_{P_1}, w_{P_2} \dots w_i$  are the uncertainties in the independent variables given the same probabilities for each independent variable, in consistent units.

Hence, the uncertainty of the result is:

$$\frac{w_{E_t}}{E_t} (100) \text{ in percent,} \quad (1)$$

## Statistical Analysis

### Arithmetic Mean

$$x_m = \frac{\sum_{i=1}^n x_i}{n} \quad (m)$$

### Standard Deviation of the Sample

$$\sigma = \left[ \frac{\sum_{i=1}^n (x_i - x_m)^2}{n-1} \right]^{1/2} \quad (n)$$

### Standard Deviation of the Mean

$$\sigma_m = \frac{\sigma}{\sqrt{n}} \quad (o)$$

### Chauvenet's Criterion

$$\left| \frac{x_i - x_m}{\sigma} \right| \leq k_8 \quad (p)$$

where:  $x_i$  = measurement<sub>i</sub>

$x_m$  = Arithmetic Mean

$\sigma$  = Standard Deviation

$k_8$  =  $d_i/\sigma$  obtained

from Table 2.

## Statistical Analysis (Continued)

### Determination of Sample Size

Using the t distribution(3):

$$\frac{\bar{x}_m - \mu_m}{\sigma / \sqrt{n}} = \pm t_{\alpha/2; v} \quad (q)$$

where:  $n$  = Sample Size

$\mu_m$  = Population Mean Life\*

$$\sigma = \left[ \sum_{i=1}^n \frac{(x_i - \bar{x}_m)^2}{n-1} \right]^{1/2} *$$

$$\bar{x}_m = \sum_{i=1}^n \frac{(x_i)}{n}$$

\* Note: For Fatigue Tests  
use log average.

$v$  = degrees of freedom,  
( $n-1$ )

$t_{\alpha/2; v}$  = Value of t statistics  
from Table 1.

$\alpha/2$  = Degree of Confidence,  
( $1-\alpha$ ) ( $\alpha = 0.7$ )

Rearranging Equation (q) :

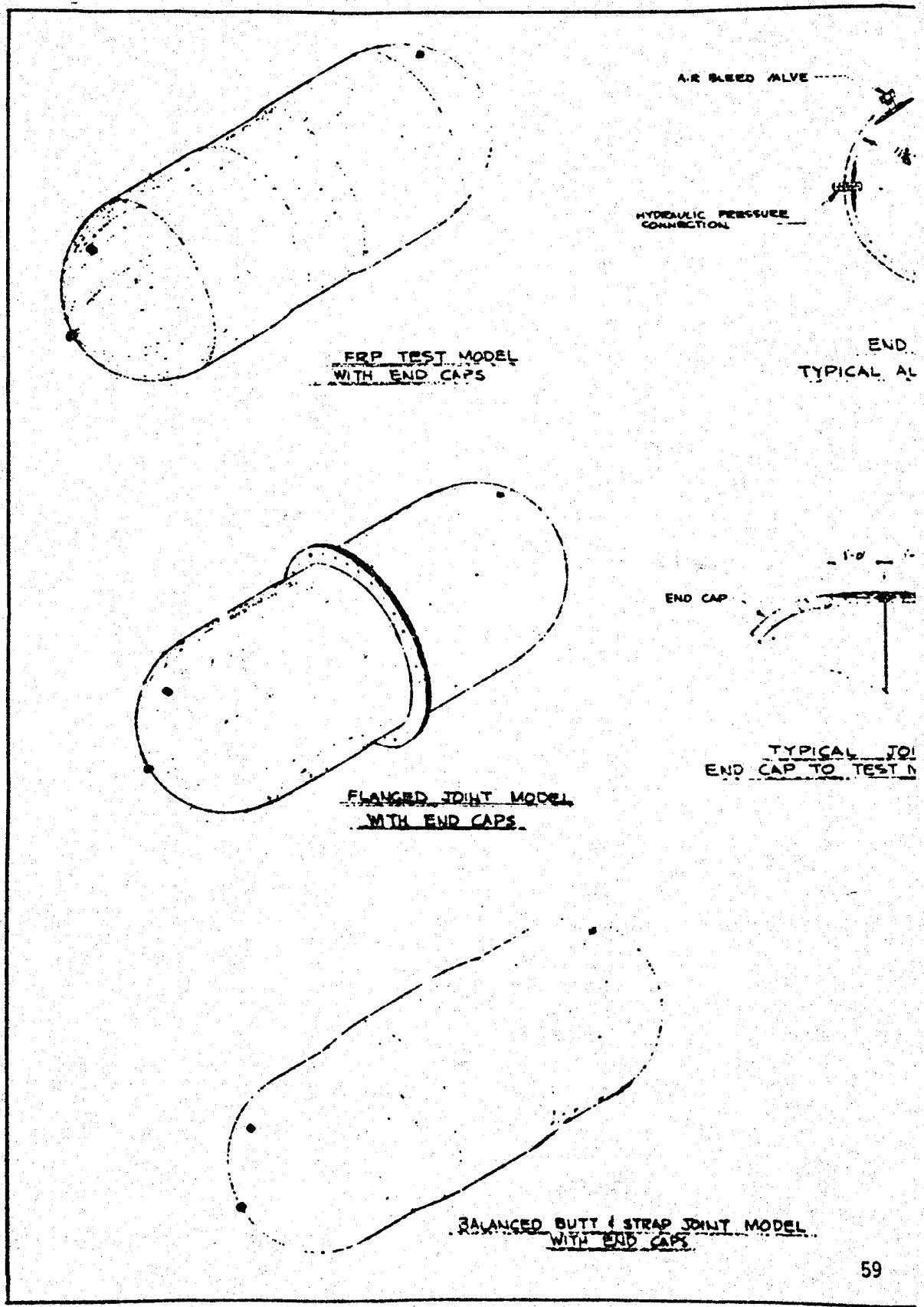
$$n = \left[ \frac{\sigma t_{\alpha/2; v}}{k_9 \bar{x}_m} \right]^2 \quad (r)$$

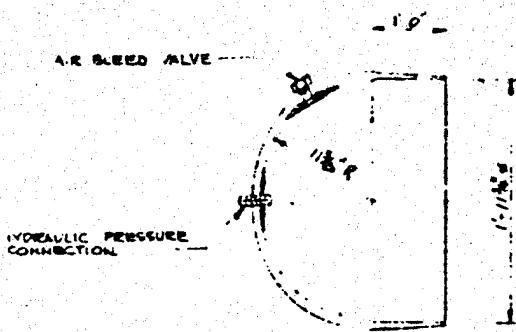
where:  $k_9$  = Maximum Percent Error (50%)  
= 0.5

### **13.4 Drawings**

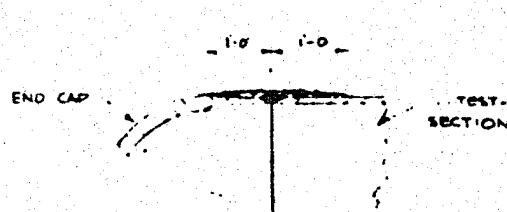
**See Attachments**



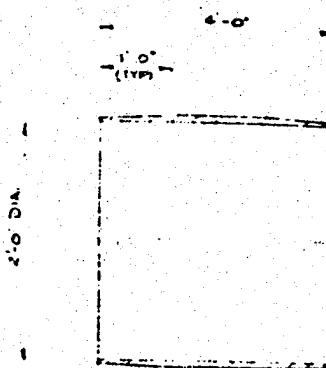




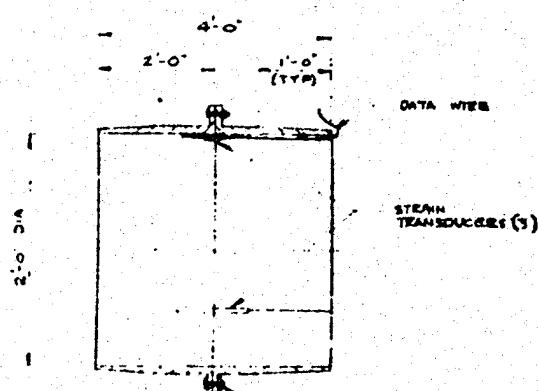
END CAP  
TYPICAL ALL MODELS



TYPICAL JOINT  
END CAP TO TEST MODEL

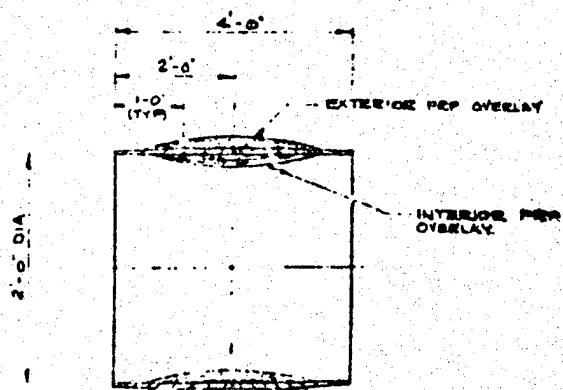


FRP TEST MODEL  
NO JOINTS



BOLTS, NUTS &  
WASHERS EA., #16 SS.

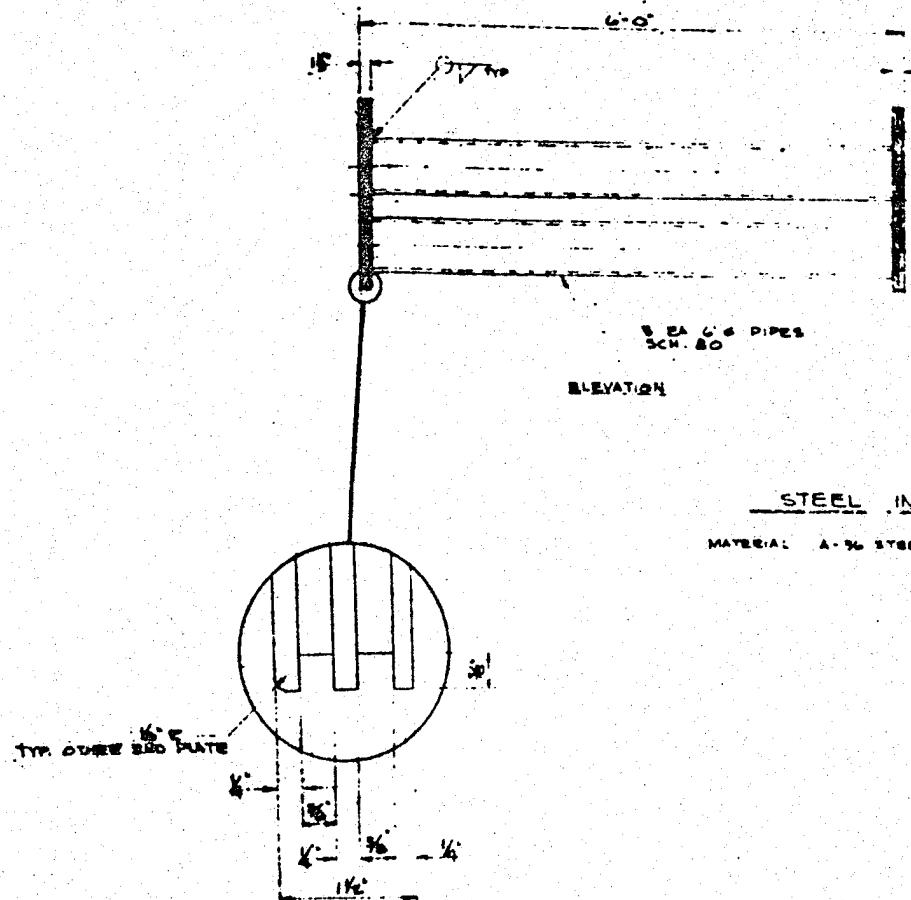
FLANGED JOINT MODEL



BALANCED BUTT & STRAP JOINT MODEL

MAP JOINT MODEL  
CARS

TEST MODELS	FRP CUP TEST MANAGEMENT PLAN	TEST FOR NO. 4
OFFICE 1074-01	REACTIVE	REACTIVE



3 EA 6" PIPES  
SCH. 80

ELEVATION

STEEL INTERNALS

MATERIAL A-36 STEEL

HYDRAULIC PRESSURE  
LINE

END CAP

16"

HYDRAULIC PRESSURE  
CONNECTION

SEE 8X6 HOLE AT  
PIPE LOCATIONS (TYP)

END VIEW

STEEL INTERNALS

AL-A-36 STEEL

4-0"  
FEP TEST MODEL

HYDRAULIC PRESSURE  
LINE

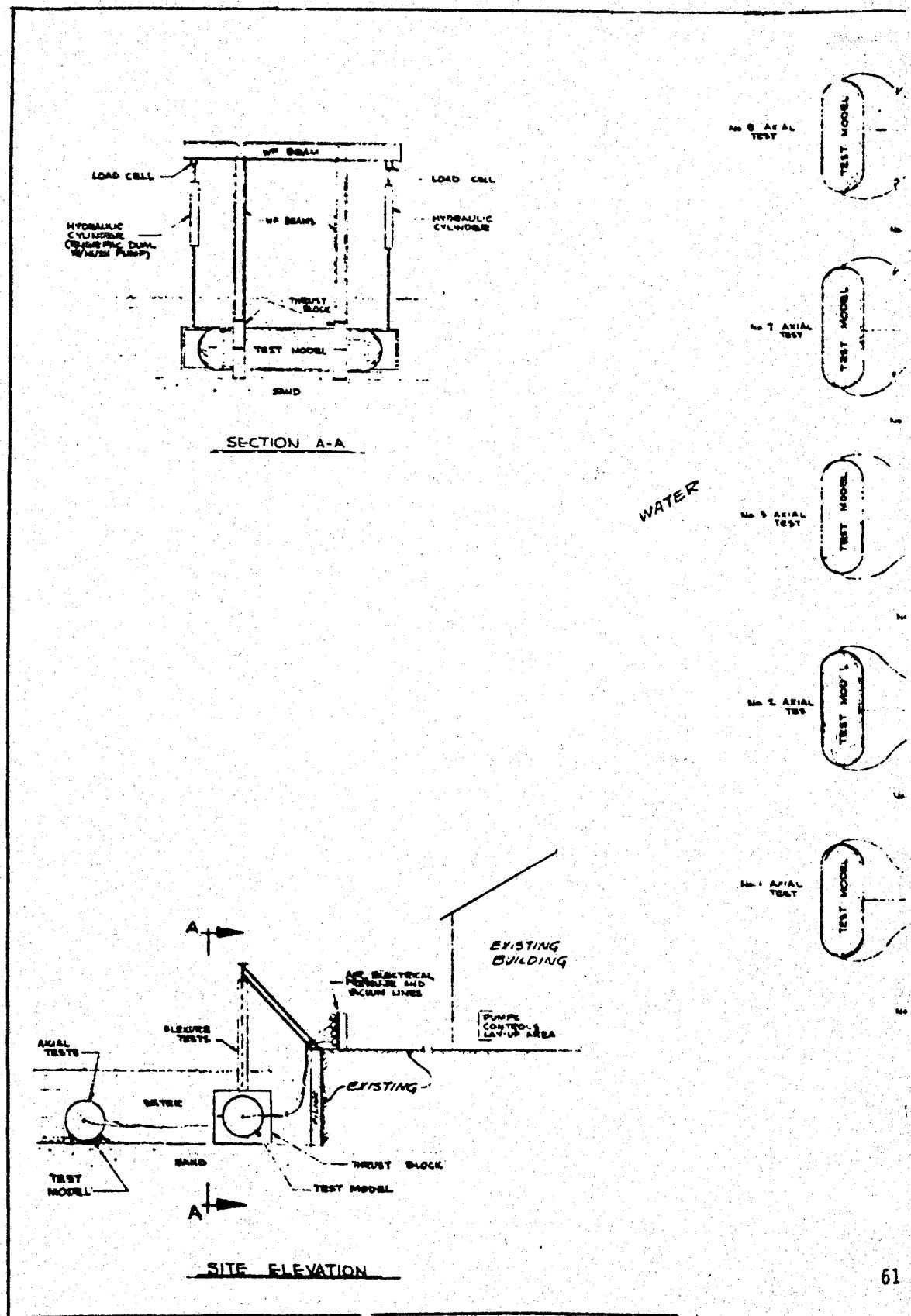
END CAP

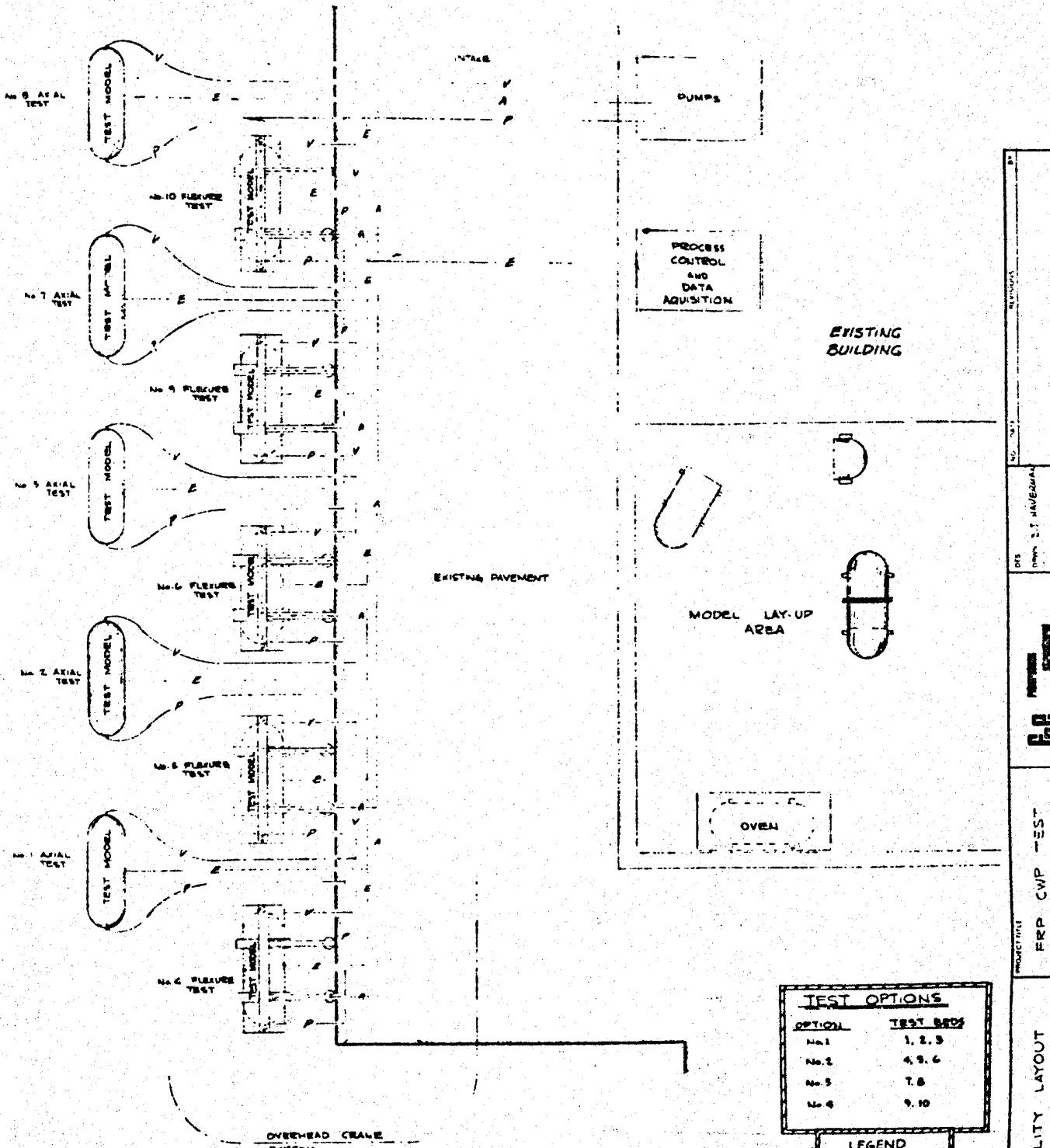
4-0"  
STEEL INTERNALS

END CAP

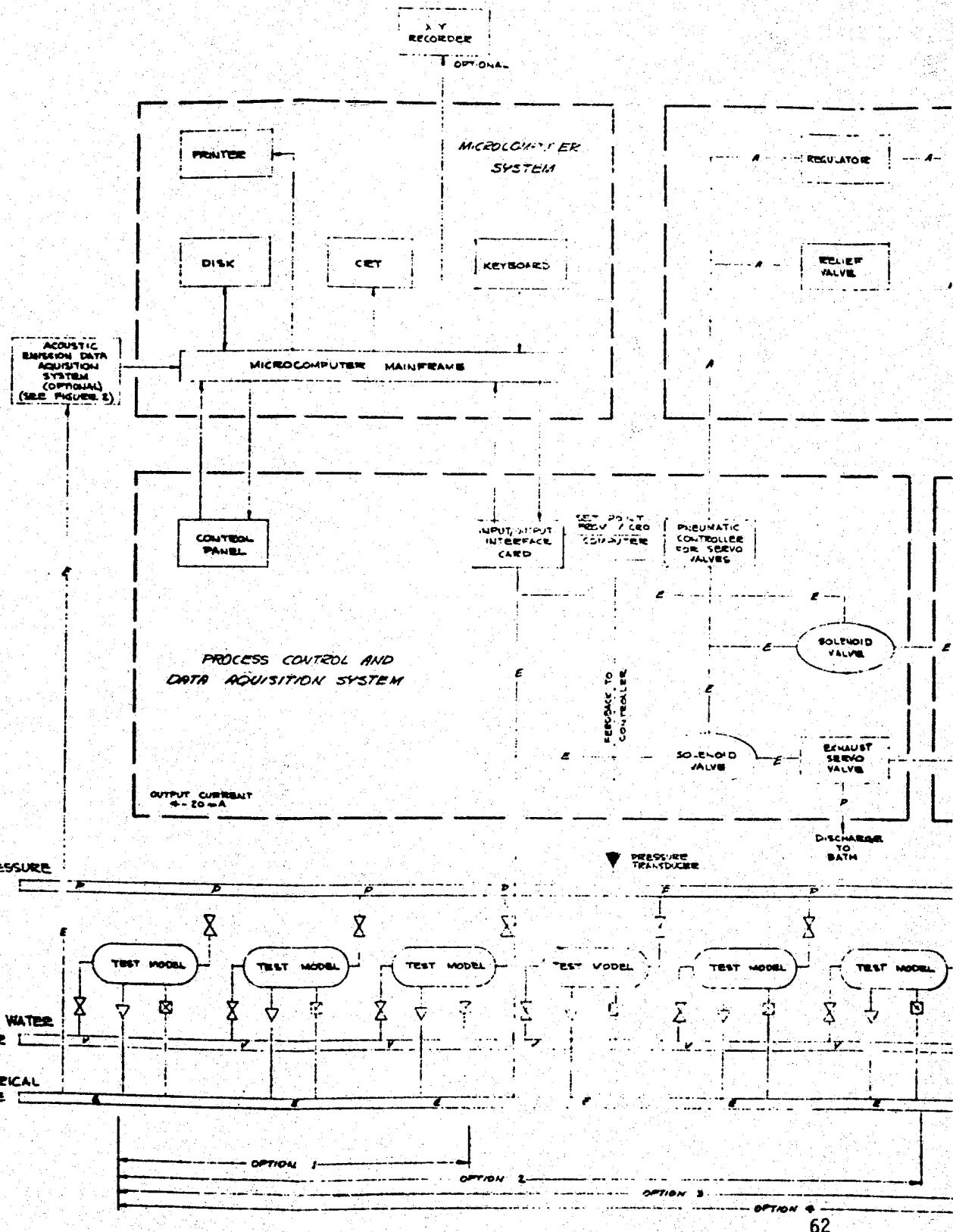
TEST MODEL ASSEMBLY

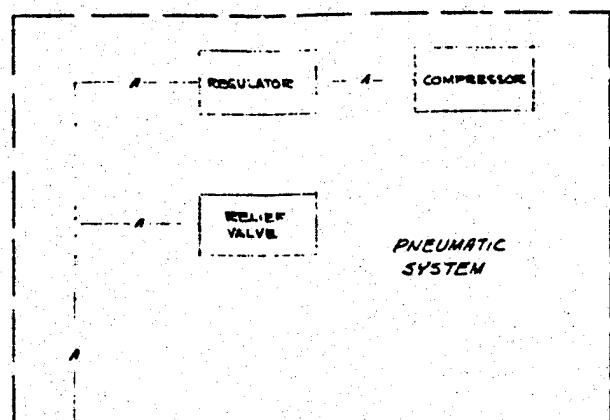
TEST MODEL	FEP CLOTH MANUFACTURER	TEST INTERNAL PLATE	TEST NO. 6A
0 FSE-1010-02	WILLIAMS WASHINGTON	WILLIAMS WASHINGTON	WILLIAMS WASHINGTON





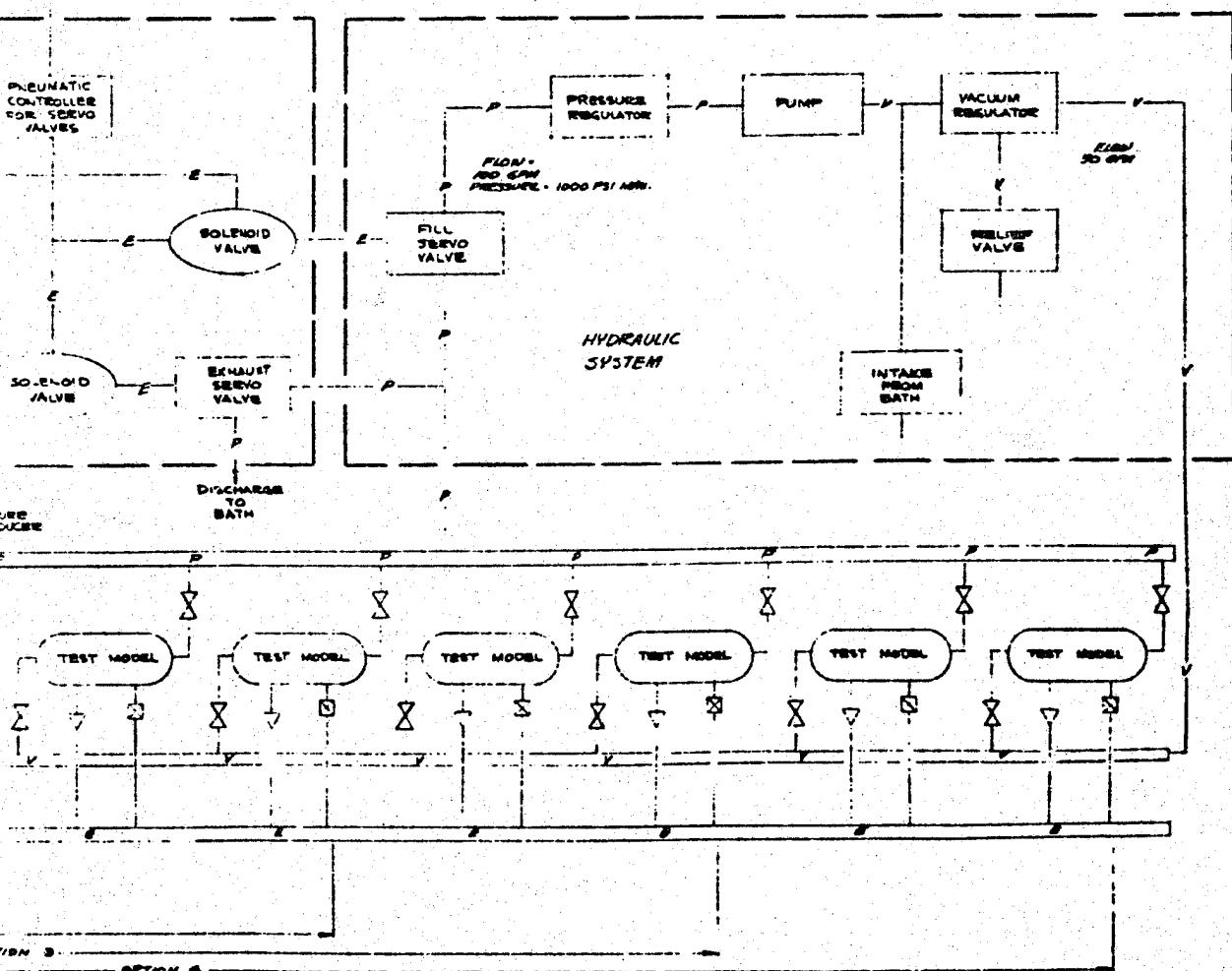
PROJECT FILE	FRP CWP - TEST MANAGEMENT PLAN
TEST FACILITY LAYOUT	LUMMI AQUACULTURE





LEGEND

- P - PRESSURE LINE
- V - VACUUM LINE
- E - ELECTRICAL
- T - STRAIN TRANSDUCER
- S - MANUAL VALVE
- A - ACOUSTIC TRANSDUCER



**SCHEMATIC DIAGRAM  
TEST SYSTEMS**

PROJECT NO. 1  
FEP CWP TEST  
MANAGEMENT PLAN  
CWP  
NOAA

005  
CHRM 3 - AVERAGE  
CHRM APP  
PROT TWO 700

REVISIONS  
DATE

#### 14.0 REFERENCES



#### 14.0 REFERENCES

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- 14) Kelly, M.P., Harris, D.O., and Pollock, A.A., "Detection and Location of Flaw Growth in Metallic and Composite Structures", Special Technical Publication 571, ASTM, 1976.
- 15) Dunegan, H.L., "Using Acoustic Emission Technology to Predict Structural Failure", Metals Engineering Quarterly, February 1975.
- 16) Telephone Conversation, Professor John F. Mandell, MIT, Dept. of Materials Science, and Jerome L. DeVilbiss, FSE, 4 October 1978 (See Reference 6).